EVALUATION OF WASTE ENGINE AND COOKING OIL FOR ASPHALT CONCRETE RECYCLING

BY

ABDULLAH AL MAMUN

A Thesis Presented to the
DEANSHIP OF GRADUATE STUDIES

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE

In

CIVIL ENGINEERING

MAY 2017

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN- 31261, SAUDI ARABIA

DEANSHIP OF GRADUATE STUDIES

This thesis, written by **ABDULLAH AL MAMUN** under the direction of his thesis advisor and approved by his thesis committee, has been presented and accepted by the Dean of Graduate Studies, in partial fulfillment of the requirements for the degree of **MASTER OF SCIENCE IN CIVIL ENGINEERING.**

Dr. Salah U. Al-Dulaijan
Department Chairman

Dr. Salam A. Zummo
Dean of Graduate Studies

8/6/17
Date

Dr. Hamad I. Al-Abdul Wahhab
(Advisor)

Dr. Hasan M. Al-Ahmadi
(Member)

Dr. Rezqallah H. Malkawi
(Member)

Dedicated To my Father and Mother

ACKNOWLEDGMENTS

At first, I am grateful to the almighty Allah for giving me the ability to accomplish this thesis. Without His mercy and blessing, nothing is possible.

I would like take the chance to express my gratitude toward Dr. Hamad I. Al-Abdul Wahhab for his sagacious supervision. He taught me how to overcome the stumbling block of research works with perseverance and adherence. His continuous motivation and problem specific directions with vast research expertise make it possible to finish the work successfully.

I am also thankful to Dr. Hasan M. Al-Ahmadi and Dr. Rezqallah H. Malkawi. I would like to thank all the members of pavement engineering research group for their support during this work. It is worthwhile to mention Dr. Muhammad Abubakar Dalhat for his valuable co-operation in the laboratory.

Last but not least, I am immensely indebted to my parents, brothers, and sisters for their endless love and psychological support. I am thankful to my mother for her encouragement for my higher study at KFUPM.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ARRA	:	Asphalt Recycling & Reclaiming Association
ASTM	:	American Society for Testing and Materials
CP	:	Centi Poise
EAPA	:	European Asphalt Pavement Association
GCC	:	Gulf Cooperation Council
HMA	:	Hot Mix Asphalt
ITS	:	Indirect Tension Strength
KSA	:	Kingdom of Saudi Arabia
LVDT	:	Linear Variable Differential Measurement
MOT	:	Ministry of Transport
MEPDG	:	Mechanistic-Empirical Design
NAPA	:	National Asphalt Pavement Association
PG	:	Performance Grade
RAB	:	Reclaimed Asphalt Binder
RAP	:	Reclaimed Asphalt Pavement
RAS	:	Reclaimed Asphalt Shingles

SAE	:	Society of Automotive Engineers
SHRP	:	Strategic Highway Research Program
VFA	:	Voids Filled With Asphalt
VMA	:	Voids in The Mineral Aggregate
WCO	:	Waste Cooking Oil
WEO	:	Waste Engine Oil
WMA	:	Warm Mix Asphalt

LIST OF SYMBOLS

C_F	:	Aggregate-Correction Factors
M_R	:	Resilient Modulus

ABSTRACT

Full Name : [Abdullah Al Mamun]

Thesis Title : [Evaluation Of Waste Engine And Cooking Oil For Asphalt Concrete Recycling]

Major Field : [Civil And Environmental Engineering]

Date of Degree : [May 2017]

This research focuses on the ability to recycle failed asphalt pavement into new pavements. This old, recyclable material or reclaimed asphalt pavement (RAP) can be reused by using a chemical agent to counteract the aging. It has been found that the use of recycled material in the construction of highways with maximum economical and practical extent for equal or improved performance is possible. There are so many potential recycling agents that can be used to reuse RAP and waste oil is one of them. The research focuses on the ability of waste engine oil (WEO) and waste cooking oil (WCO) to recycle old asphalt pavement into new pavements. The application of WEO and WCO were contemplated in pavement materials to reduce the stiffening effect of RAP. In this research, the influences of these two waste oils were investigated for different percentage of oil. A detailed laboratory investigation has been performed to evaluate the performance of waste oil rejuvenated mix and compared it with a standard mix (with no RAP) and a control mix (standard rejuvenator modified mix). For this comparison laboratory tests of Indirect Tensile Strength (ITS), durability and Resilient Modulus (M_R) have been conducted using Marshall mix design method. The results concluded from the testing indicate that for each oil, a certain percentage of that oil can rejuvenate the RAP.

WCO rejuvenated mixes outperform the standard rejuvenator with a mean ITS value of 722.3 Kpa and a mean M_R value of 1981.6 Mpa where for percent ITS loss, WCO and SAE-10 oil have similar moisture damage resisting capacity. The results obtained in the present study have shown that WCO rejuvenated pavement mixtures can outperform standard rejuvenator for a mix up to 50 percent RAP. Use of 30 to 50 percent WCO rejuvenated mixes, can save 18.5 to 32.5 percent of materials cost compare to traditional mixes whereas it is 19.99 to 36.8 percent economical compare to SAE-10 oil rejuvenated mixes. For WEO rejuvenated mixes, a mean ITS value of 616.5 kpa is observed which is smaller than the observed ITS value of 641.5 kpa for the SAE-10 oil rejuvenated mix. However, WEO asphalt mixtures exhibit higher indirect tensile strength values than the control asphalt mixtures with 7 % WEO for 30 percent RAP. WEO rejuvenated mix has a mean M_R value of 1702 Mpa which is higher than the observed M_R value of 1664 Mpa for the SAE-10 oil rejuvenated mix. Percentage ITS loss values of WEO rejuvenated samples are ranged from 4 to 18 percent. Use of 30 to 50 percent WEO rejuvenated mixes, can save 19.08 to 33.4 percent of materials cost compare to traditional mixes whereas it is 20.5 to 37.7 percent economical compare to SAE-10 oil rejuvenated mixes. So, it can be concluded that these two waste oils can provide similar or better characteristics in terms of durability, resilient modulus and tensile strength for their individual optimum oil than the mix with no RAP and standard rejuvenator modified mix. The overall conclusions indicate that the RAP rejuvenation using waste oil is an effective way of improving the performance of asphalt pavements.

ملخص الرسالة

الاسم الكامل: عبدالله المأمون

عنوان الرسالة:تقييم مخلفاتزيت الطهي وزيت المحركات لإعادة تدوير الخرسانة الإسفلتية

التخصص:هندسة مدنية

تاريخ الدرجة العلمية: ماي 2017

عن طريق استخدام (RAP)يركز هذا البحث على امكانية اعادة تدوير مواد الرصفات الاسفلتية المعاد تدويرها .لقد تبين من الابحاث (WCO) و زيت الطعام المستخدم (WEO)مادتين فاعلتين مثل زيت المحرك المستهلك ان لها ارتباط باعادة الخواص (WEO)و المحركات(WCO)السابقة انه عند استخدام المستهلك من زيت الطعام) ولكن هذه الطريقة لم تستكشف بعد فى المملكة العربية RAPالمفقودة في بناء رصيف الاسفلت المستصلح (السعودية. لذلك, هذا البحث يركز علي امكانية تحويل الخلطات الاسفلتية المستخدمة سابقا الي خلطات اسفلتية جديدة باستخدام كلا من مخلفات زيوت المحركات ومخلفات الزيوت التي تستخدم في الطعام. لقد اجريت بعض الاختبارات باستخدام العاملين لاعادة التدوير لعمل اسفلت جديد صديق للبيئة (RAP)لتقييم أداء رصيف الاسفلت المستصلح الخاصة بالمملكة .ومن المتوقع من هذا البحث المساعدة فى زيادة كمية استخدام مواد رصيف الاسفلت المستصلح المستخدم فى انشاء الطرق و التي توفر الكثير من الميزانية المستخدمة للمواد الخاصة بانشاء الطرق (RAP) و زيت المحركات (WCO) بالاضافة الى زيت الطعام (RAP)وايضا ادارة البيئة لرصفات الاسفلت المستصلحة الذى تم استخدامه .في هذا البحث, تم تقييم استخدام هذه الزيوت بنسب تركيز مختلفه. علي هذا النحو, تم (WEO) اجراء تجارب متعددة لتققيم اداء الزيوت مقارنة بالمواصفات القياسية حيث تم اجراء كلا من اختبار الشد الغير) لعينات مارشال. النتائج اوضحت انه M_R و اختبار الديمومة بالاضافة الي اختبار معامل المرونة ((ITS)المباشر). جميع الزيوت التي اختبارها RAPهناك نسبة معينة من كل زيت نستطيع اتخدامها لإعادة تصنيع الخلطة الاسفلتية (اعطت نتائج مشابهة ومحسنة في اختبارات الديمومة والشد و اختبار المقاوة عند استخدام النسبة الامثل من كل زيت. ختاما, نستطيع ان نلخص مضمون البحث ان استخدام الزيوت القديمة والمستخدمة سابقا يمكن ان يحسن خصائص SAE-10واداء الخلطة الاسفلتية واعادة تصنيعها. تتجاوزخلطات زيت الطعام المستخدم تلك المذكورة في المعيار تعادل 1981.1 ميغا باسكال. بينما بالنسبة لنسبة M_R تعادل 722.3 كيلو باسكال ومتوسط قيمة ITSبمتوسط قيمة

لهما قدرة شبيهة لمقاومة ضرر محدث بالرطوبة. وقد SAE-10, زيت الطعام المستخدم والمعيار ITSالفقدان في

بينت النتائج التي تم الحصول عليها في هذه الدراسة أن الخلطات المحسنة بزيت الطعام المستخدم تتفوق على المحسن

استعمال 30 ل 50% من خلطات زيت الطعام المستهلك RAP.%المعياري حتى نسبة خلط تصل الى استعمال 50

يمكن ان يقلل من تكلفة المواد بنسبة تتراوح بين 18.5 و 32.5% مقارنة بالخلطات التقليدية والتي تتراوح نسبها بين

. بالنسبة لخلطات زيت الطعام المستهلك, تم الحصول على قيمة SAE-10‏19.99 و 36.8 مقارنة بخلطات المعيار

. الجدير بالذكر أن SAE-10 تعادل 616.5 كيلو باسكال وهي قيمه أصغر من القيمة الخاصه بالمعيار ITSمتوسطة

خلطات زيت الطعام المستهلك الأسفلتيه أظهرت قيم لمقاومة شد غير مباشر أعلى من تلك التي تم الحصول عليها في

. إن خلطات زيت الطعام RAPحالة الخلطة المعيارية أو المرجعية بنسبة 7% من زيت الطعام المستهلك إلى 30%

وهي SAE-10 تعادل 1702 ميغا باسكال وهي قيمة أكبر من تلك الملاحظة للمعيار M_Rالمستهلك لها قيمة متوسطة

في عينات خلطات زيت الطعام المستهلك تتراوح ما بين 4 و ITS‏1664 ميغا باسكال. كما أن نسب الفقدان في

18%. أما في حال استخدام 30 إلى 50% من خلطات زيت الطعام المستهلك يمكن أن يقلل من تكلفة المواد بنسبة

تتراوح ما بين 19.08 و 33.4% مقارنة بالخلطات التقليدية والتي تتراوح بين 20.5 إلى 37.7% مقارنة بخلطات

حيث أن جميع الزيوت التي تم استخدامها اعطت نتائج مشابهة ومحسنة في اختبارات الديمومة SAE-10المعيار

والشد و اختبار المقاومة عند استخدام النسبة الامثل من كل زيت. ختاما, نستطيع ان نلخص مضمون البحث ان

استخدام الزيوت القديمة والمستخدمة سابقا يمكن أن يحسن خصائص وأداء الخلطة الاسفلتية واعادة تصنيعها.

CHAPTER 1

INTRODUCTION

1.1 Background

Recycling is defined as "the reuse, usually after some processing, of a material that already has served its first-intended purpose". In pavement engineering, recycling of asphalt pavements indicates a technology developed to replace pavement structures suffering from evident structural damage or permanent deformation [1]. The first recorded asphalt pavement recycling project was in 1915 [2]. Since that moment, it has been used as a rehabilitation technique in the highway industry and has a wide range of recycling methods regarding the technology and application process. This reclaimed asphalt pavement (RAP) may be obtained by pavement milling with rotary drum cold milling machine or from a crushing/ripping mechanism [3]. Asphalt Recycling & Reclaiming Association (ARRA) and several authors concluded that among the different available methods for recycling of asphalt pavements the most widely used techniques is hot recycling, where virgin materials and RAP are combined in different proportions and sizes [4]. In this process, RAP is combined in a central plant with new asphalt binder, new or "virgin" aggregates, and/or recycling agents to produce a recycled mix. Here RAP is softened to permit mixing with the virgin aggregates and asphalt binder and/or recycling agent. It is the most popular asphalt recycling method in the world.

Several studies on recycled mixtures concluded that the use of high RAP content is already a reality in some countries (especially Germany, USA, Holland, and Japan) [5]. Based on the data provided by 19 European countries, European Asphalt Pavement Association (EAPA) concluded that Europe used 47% of the available RAP in hot or warm mix asphalt applications [6]. In the US the asphalt industry is the country's number-one recycler and they recycle over 99 percent of RAP [7]. Here, over 50 million tons of RAP are generated annually by State Highway Agencies [8]. A survey by National Asphalt Pavement Association (NAPA) [9] estimated a total of 71.8 million tons of RAP use till 2011, 84% of which were used in asphalt applications. Some of the above-mentioned countries have started to make mixtures with 100% RAP in asphalt plants, indicating a possibility of the successful inauguration of "total recycling" in the pavement engineering [5]. The recycling of pavements has been proven as a sustainable option, due to its production process with economic and environmental benefits [10]. Those countries using RAP are getting significant financial and environmental benefits.

1.2 RAP Use in Saudi Arabia

Although many countries are trying to recycle 100 % of RAP, the use of RAP in Saudi road construction is still not very frequent. Saudi Arabia is producing millions of milled RAP each year which can be visualized by seeing its huge road length of more than 80 thousand kilometers [11]. However, despite this huge availability of RAP, it is not used in the real field. In 1984-1985 kingdom considered on the merits of RAP for the first time [12]. The first major recycling project under taken in 1986-87 to rehabilitate 60 kilometers Madinah-Tabuk highway [13]. According to the proceedings of 3rd IRF Middle East Regional Meeting held In Riyadh, Kingdom of Saudi Arabia, three international companies were assigned for road construction using RAP. They constructed roads in Tabuk, Jeddah, and Dammam using RAP. Unfortunately, the performance of those roads was not satisfactory in long run. Another practical implementation of RAP in Saudi Arabia can be found for Shaybah oilfield road in 1997. Using foamed bitumen, top 200 mm of the marl road was recycled to produce foamed asphalt pavement [14]. Since that time, the use of RAP in Saudi road construction is not significant.

There may be different reasons for not using RAP in Saudi road construction. One of the reasons is the low cost of asphalt and sufficient natural aggregate. Saudi Arabia is one of the largest producers of crude oil [15] and as a consequence it produces plenty of asphalt which can be observed by seeing its annual asphalt production (20 million barrel) [16]. Availability of cheap asphalt and natural aggregate may be a vital factor to lead local contractor reluctant to use RAP in road construction. However, this availability has a mere effect on reducing the giant budget for road construction, as the asphalt road construction of Saudi Arabia is increasing significantly. The total length of paved roads was 12,200 km in 1975, and it exceeds 40,000 km in 2000 [17]. Now, Saudi Arabia, has an extensive asphalt roads network of length reached up to 80 thousands kilometers [11]. For this continuous ongoing construction and maintenance, Saudi Arabia had invested a huge amount of money in past and this cost is expected to increase significantly in near future.

Another reason may be the prospect of using RAP for Saudi Arabia is not thoroughly explored recently. Very few researchers tried to evaluate the compatibility of RAP for Saudi road construction and more importantly, those evaluations carried out a long time ago. Among them, Arora et al., evaluated the different properties of RAP sample from Dammam-Abu Hadriyah expressway and found a better result than the traditional mix without RAP [18]. In another study, researchers evaluated the use of RAP and advocated to use RAP for Saudi road construction [19]. Hamad et al., conducted laboratory tests to compare different properties of foam recycled layers with the conventional aggregate layers and found foamed RAP mix with the best performance. They concluded that RAP can be used with foam asphalt for road base construction and this utilization of RAP in the Saudi reconstruction will result in a major cost saving [14]. RAP was also evaluated and suggested to use as sub-bases by another researcher [11]. However, those mentioned tests were carried out before the year 2000. So, insufficient recent evaluation and poor field performance of RAP at the very early construction in Kingdom may lead Ministry of Transport (MOT) reluctant to use it for real field condition. In fact, MOT does not give any guideline or specification to use RAP in road construction, so the production of recycling mixtures with RAP content is not encouraging for the local contractor. Thus, use of RAP in Saudi Arabia is very insignificant.

1.3 Need of Research

Gulf Cooperation Council (GCC) produces nearly 80-120 million tons of waste annually, 53% of which are construction and demolition waste [20]. It is considered that the largest contributor to solid waste coming from the construction sites in the Gulf is Saudi Arabia. Rapid modernization and infrastructure improvements are resulting in the production of huge amounts of demolition waste. This has consequently increased the demands for raw construction materials, such as aggregate and sand from local sources, which are utilized in construction projects. Moreover, Saudi Arabia exports aggregate to other GCC countries, such as Qatar [21]. This enormous degradation of local resources has resulted in the exigency of finding alternative sources for construction materials to reduce the pressure on natural resources. Apart from this in the eastern province of Saudi Arabia, there is a scarcity of good quality roads construction materials [22]. Husain and Assas concluded that the use of recycled materials is an urgent requirement in the present situation of the Saudi construction industry [23]. However, recycling of RAP requires special treatment for the deteriorated pavement. Different recycling agent plays a vital role in this treatment. There are so many potential recycling agents that can be used to reuse RAP and waste oil is one of them.

Along with construction debris, Kingdom of Saudi Arabia (KSA) also produces huge amount municipal waste which is depicted by its annual 15 million tons municipal waste generation [24]. Only the three largest cities of KSA are producing more than 6 million tons of waste [25]. Among those different wastes, KSA is producing huge amount of waste cooking oil (WCO) and waste engine oil (WEO). Due to the absence of recycling techniques in the KSA, a huge amount of these wastes are thrown to open landfills which is dangerous to human health and environment [24]. Consequently, serious attention is required in the use of these wastes. The most effective way to solve this problem is to reuse the waste which can be done by recycling them for road constructions. This research focuses on the ability of WCO and WEO to recycle used asphalt pavement into new pavements. In this study, different percentages of RAP were evaluated for those two waste oils. With the concern of limited natural resource and high construction cost, waste oil recycling may be a viable alternative. The objective of this research is to evaluate the potential use of the waste engine and cooking oil in recycled asphalt pavement. In Saudi Arabia, there was no previous work done to find the potential use of waste oil in RAP as a recycling agent, so it may be a great step to meet the increased demand for aggregate and binder supply in road construction of the Kingdom. It is expected that recycling construction waste will boost the economy by preserving the natural resources.

1.4 The Scope of the Research

This research focuses on the ability to recycle aged asphalt pavement into new pavements. During the maintenance or replacing of pavement, the old material or RAP can be reused as a substitute for raw materials in new roads. The use of unmodified RAP in the pavement leads to a stiffer asphalt pavement [26]. Due to oxidation RAP is brittle and stiffer, therefore to use RAP, a chemical recycling agent must be added to counteract the aging [31]. The lost properties of asphalt may be regained by rejuvenation process as the rejuvenator compensates the hardening effect [27]. Among different potential rejuvenators in this study, the effectiveness of WCO and WEO with respect to Saudi asphalt considering the local environment was evaluated. Using recycled agent in RAP is just like striking two birds with a single stone: It will not only minimize the environmental management problems of RAP, WCO, and WEO but also the desired engineering properties of the Hot mix asphalt (HMA) by economical and eco-friendly ways is expected to be improved.

1.5 Research Objective

The main objectives of the research are summarized below:

1. To find an optimum amount of cooking waste oil and engine waste oil to use in reclaimed asphalt pavement as a substitute of standard rejuvenator.
2. To evaluate the possibility of using the higher percentage of recycled asphalt pavement in road construction using waste cooking and engine oil.

1.6 Organization of the Thesis

Chapter 1 is the introduction and includes the problem statement and the main objectives of this research. Also, the need for this research has been discussed throughout the chapter. The literature review related to the thesis work is presented in Chapter 2. The literature review presents the prospect of using RAP around the world with the pros and cons of the of using RAP. In Chapter 3, the whole experimental work of the research and testing procedures of the asphalt mixtures are discussed. The analysis of results and the statistical analysis of the laboratory tests are shown in

Chapter 4. Finally, Chapter 5 presents the main findings of this research and some recommendations.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The asphalt paving industry has had great success with recycling asphalt pavements in the early 20th century [28]. However, the practice remains unpopular till the early 1970s because of decreased cost and increased supply of asphalt from many asphalt refineries [29]. But a sudden increase in oil prices and its by-product asphalt in the 1970s leaded the pavement industry interested in using RAP in HMA [30]. Along with cost minimization environmental protections also escalated the use of RAP. Numerous studies have been conducted on the use of RAP in HMA mixtures [31]. RAP has been proven to be a dependable ingredient in HMA mixtures for sustainable, cost-effective and environmentally friendly rehabilitation pavement recycling program to meet the needs of present-day users without compromising the need for our future generations.

2.2 Benefits of Asphalt Pavement Recycling

RAP use may lead to different benefits. It can serve the present and future generation by its financial and environmental benefit.

2.2.1 Financial

The use of RAP provides an economic method for asphalt construction [32]. RAP contains both bitumen and aggregates, so the use of RAP saves natural resources as well as cost [33]. The bitumen consumption is estimated to be about 85 Mt/year in the world and 90% of this consumption is dedicated to the road applications [34]. This high demand of asphalt leads to the increasing cost of asphalt which can easily visualize by seeing the increased cost of asphalt from the year 2005 to 2008. Within this three years, the cost has more than doubled from about $160 per ton to $360 or even $400 in some areas [35]. The use of RAP has become increasingly attractive to state highway agencies, especially after the increase in the cost of liquid asphalt [36]. Recycled asphalt is a huge cost saver for the local government. Contractors and municipalities recycle asphalt at $18/ton using a PT-PRO series Recycler [37]. A study concluded that different agencies of USA reduced the material cost up to 34 percent by using up to 50 percent of RAP. It resulted in a savings of 30 percent of total construction cost [38]. Since 1990, Canada saved 740,000 tons of aggregate and 42% of initial cost than a traditional rehabilitation technique [39].

2.2.2 Environmental

Bitumen is an oil-refining byproduct, so, its production is a consumption of nonrenewable natural resources with a high impact on the CO_2 emissions. Use of RAP is energy saving and ecologically safe from the viewpoint of global environment production [40]. The utilization of RAP with a view to obtaining equivalent performance of HMA, a new technology called the warm mix asphalt (WMA), is being popular in European countries [41]. This method decreases the environmental impacts by using less virgin material and reducing CO_2 emissions [42]. Since 1990, Canada has recycled 740,000 tons' of aggregate and reduced the emissions of sulfur dioxide by 9,400 tons (61%) nitric oxide and nitrogen dioxide by 440 tons (54%), and carbon dioxide by 54,000 tons (52%), compared to a traditional rehabilitation technique [39]. The required material and energy to rehabilitate asphalt pavement by using traditional hot mix asphalt are equivalent to an eco-burden of 3.45 kPt. per lane-kilometer and recycled hot mix asphalt can reduce this eco-burden by 23% [43].

2.3 Previous Studies on RAP Performance

It is evinced that the use of RAP can reduce the construction cost and it is environmental friendly but it will have no use if RAP reduces the longevity or performance of pavement. To be more specific “the performance of pavement is more important than the reduction of initial construction cost”. So, laboratory evaluation of RAP is required to evaluate its different properties. For this reason numerous studies have been carried out on the use of RAP in HMA mixtures [44]. RAP has been proven to be a reliable constituent in HMA mixtures [45].

Among different researchers Zaumanis et al., reported that the changes in Superpave performance grade (PG) of RAP binder was evaluated for six different rejuvenators and they found that the grade sum of rejuvenated RAP binder is always higher than the corresponding virgin binder [46].

In a study Tran et.al., evaluated the effect of a rejuvenator on performance and mechanistic properties of recycled binders with a mixture containing high RAP and Reclaimed Asphalt Shingles (RAS) contents in the laboratory. It was concluded that the use of rejuvenator improved the cracking resistance of the RAP mixtures without severely affecting their resistance to moisture damage and permanent deformation [47].

In another study, the ability of five different rejuvenators was evaluated. The rejuvenators were evaluated to restore the low and high temperature of polymer-modified aged binders at two different level of RAP. The true performance grades of polymer-modified aged binder were PG 76-22. Using the recommended dosage of rejuvenators, all the rejuvenated binders showed lower performance grade than that of the control binder. The rejuvenators were also found to improve fatigue resistance without substantially influencing rutting performance [48].

Another study was conducted for the performance-based properties of rejuvenated aged asphalt binders containing different level of rejuvenator at different temperatures and concluded that the rejuvenating agent can provide better or similar performance of the virgin mixtures [49].

Bennert et al., evaluated the plant-produced high-percentage RAP mixtures by overlay tester and flexural fatigue test using a softer asphalt binder grade to offset the stiff RAP asphalt binder and concluded that 75% and 50% RAP mixtures achieved better intermediate fatigue performance than the baseline 100% RAP mixture [50].

Mogawer et al., used five different asphalt rejuvenators to evaluate the performance of a 50% RAP surface-layer mixture as a function of rutting and cracking. In this study, lower rutting resistance and improved fatigue cracking resistance than all the virgin control mixture were observed. Use of polymer modified asphalt with rejuvenator were suggested for higher rutting resistance [51].

In another study, the impacts of different rejuvenators on the engineering properties of hot-mix asphalt were evaluated and it was concluded that the rejuvenating agent can improve cracking resistance, moisture susceptibility and rutting resistance of RAP mix [52].

Chen et al., developed a model to detect the content of recycling agents using various dosages of recycling agents and concluded that the performance of hardened binders can be improved significantly with the addition of rejuvenators [53].

Using molecular dynamics simulation, the effect of incorporation of recycled (aged) binder into virgin asphalt was evaluated. Scrutinizing this diffusion process it was concluded that the addition of rejuvenating agent into aged binder increase the efficiency of recycling by accelerating the inter-diffusion rate [54].

Yu et al., have conducted research on rheological properties of the virgin, aged and rejuvenator binders using dynamic shear rheometer and bending beam rheometer, and showed that the viscosity and the complex modulus of the rejuvenated binder were between those of virgin and aged binder [55].

Shen et al., studied Superpave mixtures containing RAP with softer binder rejuvenating agents by evaluating the indirect tensile strength and rutting resistance using the asphalt pavement analyzer and found better performance for the mixes with rejuvenating agents [56].

2.4 Challenges of Increased RAP Use

Several previous studies indicate that RAP can be used in the pavement and it is indeed true that small portion of RAP (usually up to 20 percent) can be used in pavement without having too much consideration. However, it becomes challenging to use the higher percentage of RAP due to its increased stiffness.

2.4.1 RAP Use: Effects on Stiffness

The use of RAP and its effects on the properties of the new pavement is well documented and it can be concluded that the use of unmodified RAP in the pavement lead a stiffer asphalt pavement [57] yet opposite was concluded by another study also [28]. Due to aging, the ratio of asphalt constituent i.e; asphaltenes to maltenes changes. The use of recycled materials can make the mix too stiff and difficult to compact which can result in premature failure [58]. Since the old material has undergone oxidation, it is stiffer and more brittle than unaged asphalt pavements, therefore in order to use RAP, a chemical recycling agent must be added to counteract the aging [59]. In other words, the lost properties of RAP must be regained to use it in road construction.

2.4.2 Asphalt Rejuvenation: Possible Solution to Stiffness

The chemical additives that blended into the asphalt mixture are known as recycling agents. Different additives are used to rejuvenate the aged asphalt (Table 2.1).

Table 2. 1. Different commercial rejuvenator [60]

Category	Examples	Description
Paraffinic Oils	Storbit®	Refined used lubricating oils
	Valero VP 165®	
	Waste Engine Oil Bottoms	
Aromatic Extracts	ValAro 130A®	Refined crude oil products with polar aromatic oil components
	Reclamite®	
	Hydrolene®	
	Cyclogen L®	
Nathenic Oils	SonneWarmix RJ™	Engineered hydrocarbons for asphalt modification
	Ergon HyPrene®	
Fatty Acids and Triglycerides	Waste Vegetable Oil	Derived from vegetable oils
	Waste Vegetable Grease	*Has different chemical elements along with triglycerides and fatty acids.
	Brown Grease	
	Delta S*	
Tall Oils	Sylvaroad™ RP1000	Paper Industry byproducts
	Hydrogreen®	Similar chemical group as liquid emulsifiers and anti-stripping agents

In general, there are two types of chemical additives that can be added to pavements containing RAP: softening agents and rejuvenating agents. The fundamental difference between a rejuvenating agent and softening is that a rejuvenating agent restores the chemical structure of aged asphalt while a softening agent blends into a mix to reduce the overall viscosity of the binder [61]. Both can reduce the stiffness of the aged binder and can be used as recycled materials [52]. The lost property of asphalt may be regained by rejuvenation that compensates the hardening effect [62]. It is evinced that a better rejuvenating effect can be attained with high amounts of resin or aromatic fractions [30]. A typical rejuvenation procedure of RAP can be observed in Figure 2.1 below:

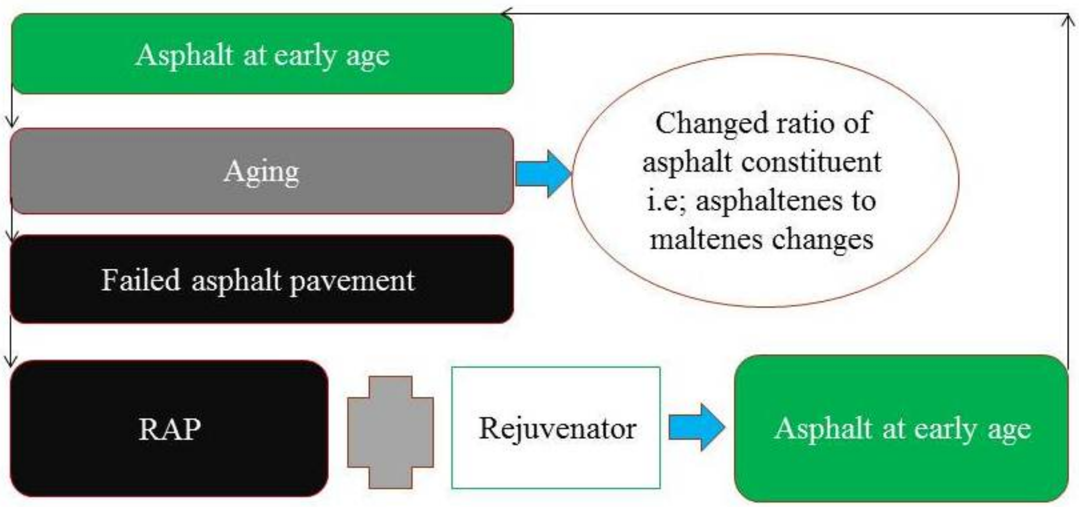


Figure 2.1: A typical rejuvenation of RAP

Several studies carried out to evaluate the rejuvenating capacity of different commercial recycling agent and were recommended for RAP rejuvenation. However, recycling RAP using waste product may be a sustainable option, which offers conservation of natural resources and economic benefits. Among different potential rejuvenator here we will evaluate the effectiveness of waste engine oil and waste cooking oil with respect to Saudi asphalt considering the local environment.

2.5 Asphalt Rejuvenation by Waste Cooking Oil

One waste rejuvenating agent that can be used to recycle RAP is waste cooking oil. Waste cooking oil is a waste product of the frying activity during cooking. Among the total produced waste oil in the world a very little amount of oil is collected and the rest major portion finds it way in the land fill and water body leaving the environment pollutant [63]. In the US 3 billion gallons of waste cooking oil are collected annually from fast food establishments and restaurants [64]. Generated WCO around the world is more than 15 million tons per year and very few of this huge amount is collected and recycled [65]. Lack of supervision can result in different environmental problem including water contamination [66]. Researchers did a lot of research projects in the reuse of waste cooking oil [67]. Several studies concluded to use WCO as rejuvenator [68] or bioaspahlt [21]. Referring to Patent by Huh, 2012, the organic acid composition in WCO is included in the family of cohesive agents [69]. Cohesive agent in RAP can reduce the viscosity and result homogeneous mixing when incorporated with new bituminous materials. This decreasing of viscosity in the binder will decrease the surface tension of binder and coated aggregate. So, it expels air curtain around aggregate and provides cohesion. It can be used as liquid or capsules form in the pavement. Usually, waste oil is blended with the binder before mixing in hot mix asphalt. It is also poured into RAP to improve the characteristics of asphalt mixture [47]. It affects different binder properties (such as penetration and viscosity). Bailey and Philips (2010) have a patent for rejuvenating asphalt using waste vegetable oil and stated that waste vegetable oil gives significant effect to different properties of asphalt, such as softening point and penetration value when mixed with the heated RAP. As previous studies inspire to use WCO for RAP recycling up to a certain extent, so it can be explored more comprehensively for the local asphalt and environment of Saudi Arabia. Moreover, KSA is producing a large amount of WCO. It has been reported that the total available waste cooking oil in Saudi Arabia is 0.39 and 4.44 million litter in 2012 and 2013 respectively [70]. So, this huge amount of WCO may be a potential source of RAP rejuvenation for Saudi Arabia.

2.6 Asphalt Rejuvenation by Waste Engine Oil

Another waste material that may be able to rejuvenate RAP is waste engine oil from cars and trucks [71]. Lubricants or cylinder oil are also considered as engine oil [72] and used to resist friction and corrosion [73]. After a certain use, the lubricating oil contains various impurities due to physical and chemical changes and can't be used for its original purpose and considered as waste oil. The properties of WEO rely on different factor like combustion process, contaminant sources such as moisture, engine wear metal particles etc. [74]. El-Fadel and Khoury (2001) made a conclusion that metal wear and high amount of lead exist in WEO. This constituent becomes the concern because of its negative effect on the environment [75]. WEO consist of non-degradable components including zinc, calcium, lead, and magnesium that are hard to be decomposed and may cause irreversible loss to the environment [76]. So, frequent dump of WEO may lead to groundwater pollution [77]. However, there are varied opinions on the feasibility of lubricating oil as an additive in asphalt cement including improving the low-temperature properties of asphalt [71]. As WEO resembles the molecular structures of asphalt, so some researchers evaluated the effectiveness of WEO as a rejuvenator [76]. Previous studies on WEO concluded that it can improve the workability and reduces the required asphalt in HMA [78]. Despite the prospect of using WEO to rejuvenate RAP, very few researches have been conducted on WEO as a recycling agent for RAP [79]. So, the prospect of this WEO can be explored for Saudi Arabia.

Saudi Arabia is considered as one of the largest automobile exporters in the world and poses 40 percent of total sold vehicle in the Middle East [80-81]. It is the largest car market in the Middle

East [82-83] and 15th largest car market in the world [84]. Observing the overall scenario of Kingdom, a study concluded that 85% people of the kingdom entirely depends on their personal vehicles for commuting and other transportation purposes [85]. So, this large number of the car is a great source of waste engine oil for KSA. A study in 1996 concluded that about 80 million gallons of automotive lubricating oils were sold in Saudi Arabia and a major portion of those oils was thrown to land indiscriminately [86]. Another study concluded that the total number of cars in Saudi Arabia increase 1.7 times in 10 years from 2005 to 2014 [87]. So, it is obvious that the total used lubricating oil is significantly higher than the observed amount for 1996. Thus, the chances of pollution are also much higher. As during routine oil change, three to four liters of WEO can be obtained from a single vehicle so this huge amount of car can provide a significant amount of WEO for RAP rejuvenation. It is obvious that this waste oil may have different hazardous metal in it. Table 2.2 indicates the properties of WEO.

Table 2.2: Characteristics of WEO

Metal	Avgerage (in ppm)	Standard deviation (in ppm)
Fe	501.60	201.96
Cr	44.20	9.92
Cu	2.08	0.60
Mg	278.15	76.67
Ni	4.18	1.41
Pb	4068.75	840.61
Zn	830.85	77.60
Ca	1765.95	536.97
Ba	4.38	1.50

Mshammad et al., summarize this table as a typical analytical result for 20 WEO samples in Saudi Arabia [88]. Those samples were collected from different filling station throughout the kingdom during winter and summer. However, the hazardous metal present in the WEO is acceptable to use WEO as a rejuvenator for RAP modification [27].

2.7 Previous Evaluation Waste Oil in RAP

Bailey and Philips (2010) conducted a study about the use of vegetable oil, and the result showed that it can decrease the stiffness of the aging mixture [89]. An investigation on the effect of cold mix asphalt using a different percentage of waste oil concluded about 28% decreased stiffness compared to the control samples (without waste engine oil) at the temperature of 40^0C [90]. Dedene conducted the rutting resistance test at the temperature 58^0C with 25% RAP and for two different level of WEO and concluded that it can increase the rutting resistance compared to the neat sample [91]. Tran et al., revealed the implementation of the emulsion obtained from naphthenic crude stock (Cyclogen® L) in RAP and found more resistant against low-temperature cracking [92]. Those findings show that the application of waste oil will be effective if used with the higher percentage of RAP.

2.8 Summary

There are many potential recycling agents that can be used to reuse RAP and waste oil is one of them. A large amount of untreated oil that is discarded on landfill prior to any treatment has a prominent negative impact on the environment. A significant amount of this discarded oil finds it way in water. A thin surface layer produced on the water by oil hinders the frequent movement of oxygen and sunlight in the water resulting in the disruption of aquatic life [3]. Despite affecting the water quality, it hampers normal aquatic ecosystem. With the concern of high construction cost and limited natural resources, waste oil recycling is becoming the viable alternative in mitigating these problems [75]. During the use of RAP, small amounts of waste oil blended in the mix may prove beneficial by offsetting the increased stiffness and producing a pavement with similar characteristics to one made of virgin materials. Waste oil may be economical than a traditional rejuvenating agent for similar rejuvenating capacity. At the same time use of waste oil for the higher percentage of RAP in road pavement may be beneficial to meet the increasing demand of asphalt pavement in Saudi Arabia.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Introduction

The whole work was divided into three phases. The first phase includes material collection and processing. The second phase includes RAP and aggregate characterization. In the third phase, waste oil rejuvenated RAP mix was prepared based on the MOT specification. Among different available mix design procedure, Marshall mix design method was followed. Those mixes were tested for durability, stability, resilient modulus and indirect tension test (ITS). Figure 3.1 shows a flow chart of the whole work.

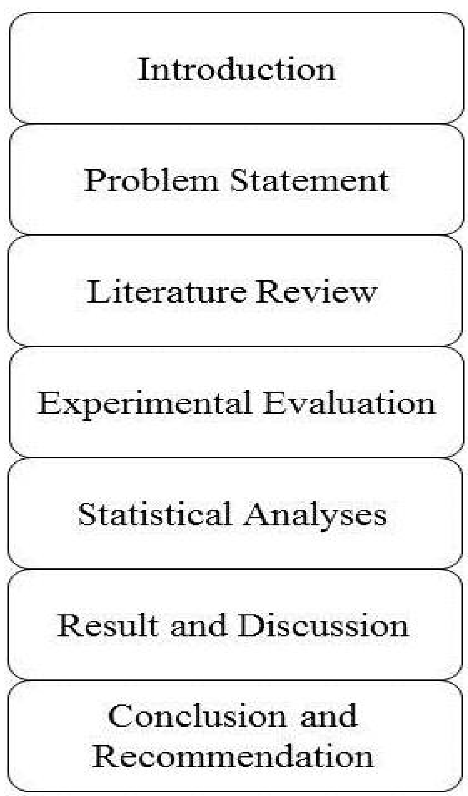


Figure: 3.1 Brief flow chart task

Figure. 3.2 shows a flow chart with minute details at each step of the experimental work of this research.

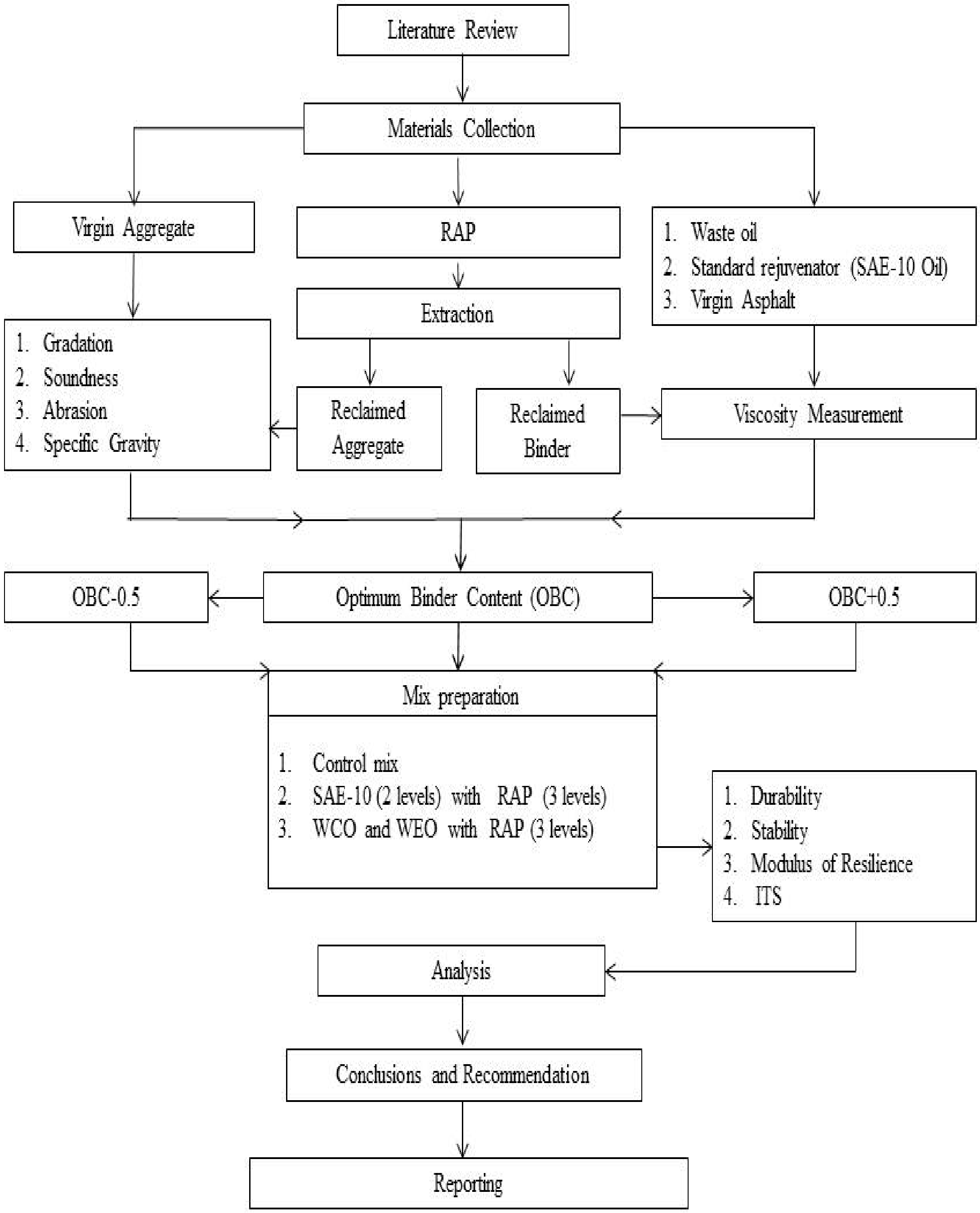


Figure 3.2: Flowchart showing details task at each step

The used materials including the base asphalt, aggregates, and waste oil were obtained from the local area of Dammam. After the characterization of the used materials, the mix was prepared for the different combination of RAP mix and rejuvenator. In this study, Marshall mix design was used to obtain the optimum binder contents for all asphalt mixtures. The following sections have discussed some of these stages in details.

3.2 Material Collection and Processing

Several tests were carried out for RAP, binder, waste oil, rejuvenator and asphalt aggregate mix after material collection. Material collection and preparation were done as below:

3.2.1 Virgin Aggregate

Aggregates for HMA are required to be hard, tough, strong and durable to resist heavy traffic as well as harsh environmental. The local aggregate was used in the asphalt mixture. Those aggregates are mainly limestone and collected from a local company namely "Al Yamama Company". The most important properties of the aggregate were evaluated in the laboratory to make sure that it meets the current specifications of MOT in Saudi Arabia. Some of the basic test like The Los Angeles (L.A) Abrasion Test (ASTM C131), Soundness Test (ASTM C88), Coarse and Fine Aggregate Angularity Test (ASTM D5821), Percent Flat and Elongated Particles (ASTM D4791) were conducted for this aggregate.

3.2.2 Recycled Asphalt Pavement

Locally recycled asphalt pavement was collected from a road construction site of King Fahd University of Petroleum and Minerals (KFUPM). This road connected the administrative building and main entrance. After the collection of representative RAP sample, it was processed. The processing includes the removal of any deleterious materials such as plastic, unwanted debris, lumps, grass and road marks by visual inspection. Subsequent tests were conducted on these samples which are representative of the field samples under real life situation.

3.2.3 RAP Characterization

RAP is a heterogeneous mixture of asphalt binder and aggregates; however, for research purposes, it is necessary to isolate the binder from the aggregates. Two options are recommended for determining RAP asphalt content and recovering aggregates: solvent extractions and the ignition method. In the first method, to separate the binder from the aggregates, the binder must be chemically stripped from the aggregates, ultimately leaving only the aged binder for lab testing. Previously conducted ASTM D 2172 procedure for extracting the asphalt binder from the aggregates indicated the properties of aged binder [93]. However, ignition method can provide more precise indication of existing asphalt content in HMA mixtures than solvent extraction methods, without affecting the aggregate gradation significantly [122]. In this study, the aggregate from RAP sample was separated through Ignition Method (ASTM D 6307). Usually, the obtained percentage of asphalt using this method is significantly higher than the actual value, so it is important to use the aggregate correction factor. This factor is typically consistent over time for the aggregate materials of similar deposits or quarry [35]. Therefore, an aggregate correction factor was obtained in the laboratory for the aggregate.

3.2.4 Waste Oil and Rejuvenating Agent

Recycled waste engine oil was collected from different automobile service station of Dammam while waste cooking oil was collected from food department at KFUPM. Some other sources for WCO are various restaurant and cafeteria in Dammam-Khobar area. Both waste oils were filtered prior to use as a rejuvenating agent. A standard rejuvenating agent SAE-10 was collected from local distributor "Saudi-Bahrain Center". Finally, viscosities of the collected rejuvenators were measured.

3.3 Mix Design and Preparation of Asphalt Mixtures

This study was conducted employing the Marshall method of mix design (ASTM-D1559). Marshall mix design optimizes the mix based on the Marshall stability and flow test. Two test series used the selected modifiers, i.e. waste cooking oil and waste engine oil and the corresponding recycled asphalt mixture are henceforth designated as WCO and WEO respectively. Each of the above mixtures comprised RAP, modifier of suitable quantity as determined, virgin aggregate to correct aggregate grading deficiencies in RAP and, virgin asphalt to meet asphalt demand of additional aggregate including the reclaimed pavement. Commercial rejuvenator SAE-10 oil was used to prepare another mix which is designated as Control (SAE-10 oil mix). Control mix was used as a basis of comparison with other test series employing the recycling mixtures. To evince different properties of the rejuvenated mix, a standard mix without any recycled aggregate were also prepared. This is remarked as the Stand. Mix (standard mix). The quantity of new asphalt to be added to the recycled mixture equaled the calculated asphalt demand minus the quantity of asphalt in the reclaimed asphalt pavement, and minus the quantity of modifier used.

Prior to mixing, RAP, virgin aggregate, and virgin asphalt were heated separately for a period of 2 hours at 146°C. This 2 hours heating time are considered as the standard procedure [94]. Previous studies concluded that preheating conditions can change the performance of the new mix [95]. So, this heating period is very important for RAP mix. RAP was heated in a covered pan and during the last 15 minutes, the specified amount of modifier was placed in a closed container and heated to approximately 94°C. At the end of two hours, the constituents were transferred to the mixer. It is to be mentioned that mixing can be done in a different manner like cold, heated in a microwave, heated in an oven in a covered pan, and heated in an oven in a non-covered pan. Basueny et al., showed that they cannot propose a specific method from the four methods to be used in the laboratory since each method has its advantage and disadvantages from the degree of handling and the required time saving [96].

In this study, while the modifier was added to the RAP for mixing, virgin aggregate and virgin asphalt were immediately introduced to the mixer. Asphalt cement was heated to produce a viscosity of 170±20 cSt for mixing and a viscosity of 280±30 cSt for compacting temperature. The mixing was carried out in an automatic mixer and continued for a total period of 2 minutes as it was found to be adequate to give a homogeneous, well-coated mix, without any appreciable drop (less than 6°C) in temperature. The mixture was covered and placed back in the oven at 130°C for 30 minutes prior to compaction. Compaction was carried out with Marshall hammer giving 75 blows on each side. To determine the optimum binder content for each test series, Marshall testing was conducted at 60°C. Three specimens for each combination of aggregates and bitumen content is prepared. Approximately 1200g of the sample was compacted with a target to make a specimen of 2.5±0.05 inch in height. The stability is measured for a maximum load which is designated as stability, supported by the test specimen at a loading rate of 50.8 mm/minute. An attached dial gauge indicates the deformation along with maximum load prior to failure.

In addition, Marshall stability losses of the samples were also measured following the specification ASTM D 1559 (2004). It is an indicator of moisture damage through Marshall method. The way to perform it is to prepare 6 samples at first. Those sets are divided into two subsets, and then determine the stability of one set i.e.; 3 samples were kept at 60^0 C in water for 30 to 40 minute where other samples are kept in the same condition for 24 hours. Finally, that two stability are compared in term of percent stability loss. The maximum allowable value of percent stability loss is 20%. The percentages of air voids in the specimens were determined from the bulk specific gravity of the specimens and the maximum theoretical specific gravity of the void less mix. The optimum asphalt content of the mix was then calculated as the numerical average of the values of the asphalt contents determined corresponding to maximum stability, maximum unit weight and 4 percent air voids in accordance with the recommendations of the Asphalt Institute (1979) [97].

3.4 Mixtures Testing

In a real field, HMA is subjected to a variety of traffic loads and different environmental conditions, so it must be tested under these conditions to ensure the appropriate characteristics at the different environmental condition. In this study, some of the basic engineering properties of the mixtures were carried out in the laboratory to evaluate the overall quality of the mixtures for different percentage of RAP rejuvenated by different percentage waste oil to achieve the objectives of this research. Three different percentages of RAP (30%, 40%, and 50%) were investigated at three different binder contents (optimum, optimum + 0.5%, and optimum - 0.5%). Previous studies concluded that selections of binder content above and below the optimum level dictates the effect of binder content on mixture performance and volumetric properties of RAP mix. [98]. After the selection of design parameters, the required samples for the testing stage are compacted and prepared. To evaluate the main mixtures characteristics, four types of testing are conducted. The used tests are listed in Table 3.1

Table 3.1. List of the mixtures tests

Test	Objective	Specification
Marshall Stability Test	Optimum binder content	ASTM D6927
Tensile Strength	Indirect Tensile Strength	ASTM D6931
Resilient Modulus	Resilient Modulus	ASTM D-4123
Durability Characteristics	Durability (Moisture Sensitivity)	AASHTO T-245

The used samples in these tests have a diameter of 4 in. and height of 2.5 in. The same samples for each mixture type are used for the resilient modulus test and the indirect tensile strength tests since that the resilient modulus tests is a non-destructive test. The experimental design is shown in Table 3.2:

Table 3.2: General experimental design setting of various combinations.

Mix Type	Level of Asphalt Content	Percent of RAP		
		30	40	50
WCO Mix	Optimum+0.5	✓	✓	✓
	Optimum	✓	✓	✓
	Optimum-0.5	✓	✓	✓
WEO Mix	Optimum+0.5	✓	✓	✓
	Optimum	✓	✓	✓
	Optimum-0.5	✓	✓	✓
SAE-10 oil Mix (Control Mix)	Optimum+0.5	✓	✓	✓
	Optimum	✓	✓	✓
	Optimum-0.5	✓	✓	✓
Standard Mix (Fresh Mix)	Optimum+0.5	✓		
	Optimum	✓		
	Optimum-0.5	✓		

3.4.1 Indirect Tensile Strength (ITS) Test

The tensile properties of HMA are of the interest to pavement engineers because of the problems associated with cracking. Though HMA has a higher compression-resisting capacity compare to tension, yet it plays significant indication to identify cracking properties of the pavement. A lot of research work has been reported on different characteristics of bituminous pavements relating the tensile strength of bituminous mixtures [99]. Indirect tensile strength (ITS) is considered as the potential test method and can be well related to fatigue cracking in asphalt pavement [100]. A higher tensile strength and strain prior to failure is an indication of higher crack-resisting capacity [101]. Higher ITS value also indicates higher resistance to low-temperature cracking [102]. So, identifying IDT will be an important parameter for our evaluation. Previous studies indicated an increasing of IDT due to the presence of RAP in HMA [103]. This test method is performed in accordance with ASTM D6931 at a temperature of 25^0C. In this test, the 101-mm diameter cylindrical samples are kept between two loading strips (13 mm). A constant rate of compressive load is applied (51mm/minute) vertically to generate a relatively uniform tensile stress across the diametrical axis of a cylindrical specimen. Loading continues until it fails. Corresponding load at failure point is recorded and the tensile strength is measured following the equation below:

ITS = 2 Pmax / (3.1416 x t x d) **(Eq. 3.1)**

Where,

P_{max} = Maximum applied load, (N)

t = Thickness of specimen, (mm)

d = Diameter of specimen, (mm)

3.4.2 Modulus of Resilient (M_R) Test

The modulus of resilient (M_R) is used to determine the stiffness loss and elasticity modulus of asphalt mixtures. It is an important parameter to design flexible pavement [104]. It dictates the load carrying ability of the asphalt pavement [105] and an assessment of resistance to permanent deformation or rutting [106]. Several studies have focused on evaluating the effect of different factors on M_R values [107] and different materials on the stiffness of asphalt mixtures [108]. Previous studies concluded that M_R values changes due to change in the percentage of RAP and recycling agent in the mix [109]. So, this test can dictate an important indication for our mix. In this research, the test is conducted on the 25°C temperature with 0.33 Hz loading frequency based on ASTM D-4123. The resilient modulus of asphalt mixtures is investigated by the diametric resilient modulus device "Servo-Pneumatic Universal Testing Machine". The setup of the machine can be observed in Figure 3.3. Digitally generated waveforms are applied by the actuator generates repeatable stress variations in test specimens to simulate the moving traffic load.

Figure 3.3: Servo-Pneumatic Universal Testing Machine

So, the experimental specimen responses in term of dynamic stress and corresponding strain. It is basically a repetitive load test using the stress distribution principles of the indirect tensile test. In this test, the loading consists of having sine pulse with a duration of 0.1- second followed by a rest period of 0.9-second duration which was followed in this study with linear variable differential transducers (LVDTs) placed along the specimen diameter. This set up generates a uniform state of tensile stresses perpendicular to the load direction. The resulting horizontal dynamic deformation across the horizontal plane of the sample is measured as the output of the test. For each mixture type, three samples are tested with two diameter positions and readings are taken for three number of repetitions.

3.4.3 Durability Test

The durability of pavement is the ability to resist the effects of the different environmental conditions with no major deterioration for a long period of time under the traffic loads [110]. It requires maintaining the serviceability of pavement over a specified time. The safe performance of a structure or a portion of a structure for the designed life expectancy depends on increasing durability against water-induced damage. The performance of flexible pavement is regulated by moisture damage [111]. Moisture damage in asphalt pavement indicates the loss of adhesion between asphalt binder and aggregate surface due to moisture [112]. This loss of adhesion due to moisture results in degradation or particle disintegration and eventually weakens the stiffness of the pavement. Therefore, a moisture damage prone pavement could eventually result in any of the failure modes and it is very critical to the long-term performance of asphalt pavement. Previous studies concluded that RAP may increase the resistance to moisture damage [113] where the inverse was also concluded by another study [114]. To evaluate the durability, a mixture is subjected to environmental conditions then the mixtures are tested using ITS test before and after the conditioning process. In this research, the moisture susceptibility (durability) is conducted following the AASHTO T245. The degree of susceptibility to moisture damage is determined by preparing a set of the sample. The way to perform this test is to prepare six samples. Those set are divided into two subsets, and then the tensile strength of one set is determined i.e.; three samples at room temperature where another set is kept at 60^0C water for 24 hours and followed by 2 hours in 25^0C, then bring to the test temperature to determine the wet (conditioned) tensile strength. To analyze the results, the calculation of tensile strength ratio (TSR) by taking ratio from average wet tensile strength and average dry tensile strength. The minimum value of TSR is 80%.

TSR = ITS (Wet) / ITS (Dry) **(Eq. 3.2)**

Where,

TSR	=	Tensile strength ratio, (%)
ITS (Wet)	=	Indirect tensile strength for the wet samples, (P_a)
ITS (Dry)	=	Indirect tensile strength for the dry samples, (P_a)

3.5 Statistical Analysis

To investigate the significance of the effect of different oil on the RAP mixtures characteristics and the effectiveness of waste oil in compare to the standard rejuvenating agent mix and standard mix, statistical analyses were performed. These statistical analyses are important to investigate the results and parametric relationships of this research. The obtained experimental data was analyzed using statistical techniques such as analysis of variance (ANOVA) to determine the significant and most prominent percentage of rejuvenator. This indication from ANOVA will be helpful for the selection of waste oil percentage in RAP modification. Statistical analysis software Minitab 16 was used for those analyses.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Introduction

The results of laboratory tests are presented and discussed in three main parts following the experimental program discussed in Chapter 3. The first part of this chapter includes the characteristics of the raw material used in this study. The results of the asphalt mixtures testing which include the mixtures design, indirect tensile strength test, resilient modulus test and durability test in addition to the findings of the statistical analysis. Finally, a summary of the mixtures testing results is provided at the end of each part.

4.2 Materials Characterization

In this study RAP from a single source was rejuvenated using two waste oil and one commercial rejuvenating. This chapter describes the material acquisition and their processing with the following subsection.

4.2.1 RAP Characteristics

Previously conducted extraction and laboratory performed ignition method measure the asphalt content of HMA. As mentioned that ignition method requires aggregate-correction factors (C_F) and it is typically consistent over time, therefore, an aggregate correction factor was obtained in the laboratory for Dammam aggregate. Once the correction factor is known then the amount of asphalt content in the RAP was obtained following the formula below:

$$\text{Actual asphalt content in RAP} = \text{Observed asphalt content by ignition} - C_F \qquad (4.1)$$

Where C_F = Aggregate-correction factor

Following the equation, 4.1 observer asphalt content is listed below in Table 4.1. It is to be mentioned, that property of aged asphalt included in Table 4.1 by solvent extraction method was obtained from the previous research conducted by Hamad et. al. [93].

Table 4.1: Properties of RAP

<table>
<tr><td colspan="3">Ignition Method (ASTM D 6307)</td><td>Solvent extractions
(ASTM D 2172)</td></tr>
<tr><td>Number of observation</td><td>Asphalt content % by total mix</td><td>Aggregate-correction factor (C_F)</td><td rowspan="7">Absolute viscosity at 60^0 C

Absolute viscosity =43000 poise</td></tr>
<tr><td>1</td><td>6.23</td><td>1.23</td></tr>
<tr><td>2</td><td>6.2</td><td>1.17</td></tr>
<tr><td>3</td><td>6.17</td><td>1.18</td></tr>
<tr><td>4</td><td>6.2</td><td>1.22</td></tr>
<tr><td>Average</td><td>6.2</td><td>1.2</td></tr>
<tr><td colspan="3">Percentage of asphalt = 5.0 percent</td></tr>
</table>

Once the RAP passed ignition method, then the residue was collected as reclaimed aggregate. This aggregate was further analyzed for gradation. The gradation of RAP and reclaimed aggregate can be found in Table 4.2. This table dictates that the collected RAP from the site was significantly coarser, yet some fine portion of RAP was also found in the RAP but that was very insignificant. As previous studies conducted on RAP suggested to use coarser RAP, so we only used coarse RAP [95]. Finally, the specific gravity of the reclaimed aggregate was measured which can be observed in the Table 4.3. The Bulk specific gravity (BSG) of the RAP aggregate cannot be directly measured as BSG of the RAP aggregate recovered from the ignition oven is significantly lower than that of the original aggregate [115].

Table 4.2: Gradation of RAP and reclaimed aggregate

Parameter	Percent passing	
Seive size (in mm)	RAP	Reclaimed aggregate
19	100	100.00
12.7	15	72.22
9.51	5	40.28
4.76	0	12.50
2.00	0	6.67
0.42	0	4.44
0.177	0	2.22
0.074	0	0.50

In this study the source of RAP is known and original construction records are available. So, the obtained details of the aggregate properties can be found in Table 4.3. However, the details of BSG measurement for RAP can be found in Reference [115].

Table 4.3 : Bulk specific gravity (BSG) of aggregate RAP

Aggregate type	BSG
Coarse Aggregate	2.425
Fine Aggregate	2.575

4.2.2 Rejuvenator Characteristics

Three different rejuvenating agents are used in the study. Measured kinematic viscosity and the specific gravity along with some basic characteristics obtained from manufacturers and laboratory evaluation are included in Table 4.4.

Table 4.4: Properties of rejuvenators.

Rejuvenator	Specific gravity (g/cc)	Oil type	Refined or Waste	Viscosity (cP) at 60 ^{o}C
Waste Cooking Oil	0.917	Vegetable	Waste	12.5
Waste Engine Oil	0.872	Petroleum	Waste	50
SAE-10 Oil	0.8598	Petroleum	Refined	37.147

The quantity of modifier to be added was determined from the consideration of softening the extracted asphalt to a target value of viscosity. Target viscosity is equal to the viscosity of the virgin binder which is obtained by using the blending chart [116]. A linear relationship was obtained between the logarithm of blend viscosity and the modifier percentage concentration in the blend. The results showed that 20 percent of WCO by weight of total fluid were adequate to reduce the viscosity of the aged asphalt to that of the virgin asphalt. However, to visualize the effect of rejuvenator the level of rejuvenator was varied by 7 percent above and below the obtained level from blending chart. For WCO used percentages of oil were 13%, 20% and 27%. For WEO and standard rejuvenator, obtained percent of fluid was 13 percent of the aged binder. Similar to WCO, this level was also varied for WEO and used percentages of WEO were 7%, 13% and 20%. For standard rejuvenator, only 7% and 13% of SAE-10 oil were used.

4.2.3 Aggregate Characteristics

The characteristics of aggregate can be observed in Table 4.5 and it indicates satisfactory results obtained as per the requirements of MOT. The results of the coarse and fine aggregate testing are summarized below:

Table 4.5 Aggregate properties

Coarse Aggregates		
Test name	**Results**	**Specifications**
L.A. Abrasion (%)	31.5%	40%.Max
Soundness (%)	24%	25%.Max
Angularity (%)	98%	90%.Min (2 fractured faces or more)
Flat and elongated particles ratio (%)	2.3%	(5:1 ratio) 10%.Max
Bulk specific gravity	2.503	-
Apparent specific gravity	2.678	-
Absorption (%)	2.60	-
Fine Aggregates		
Test name	**Results**	**Specifications**
Sand equivalent value	57%	40%.Min
Bulk specific gravity	2.53	-
Apparent specific gravity	2.69	-
Absorption (% Abs)	2.35	-

4.3 Aggregate Blending

Designing mixes containing high RAP requires special attention to ensure minimum VMA. RAP is somewhat finer than virgin aggregate, hence it is recommended that RAP used in recycled asphalt should be as coarse as possible and the fines (< 0.075mm) should be minimized [95]. Previous studies also recommend adjusting the amount of virgin aggregate to account for the RAP aggregate to meet a final blend gradation to meet specified volumetric properties [117]. So, it is better to blend the coarser RAP with finer fractions of virgin aggregate to meet the specification limits. Here the gradation was adjusted to follow the specification (Figure 4.1).

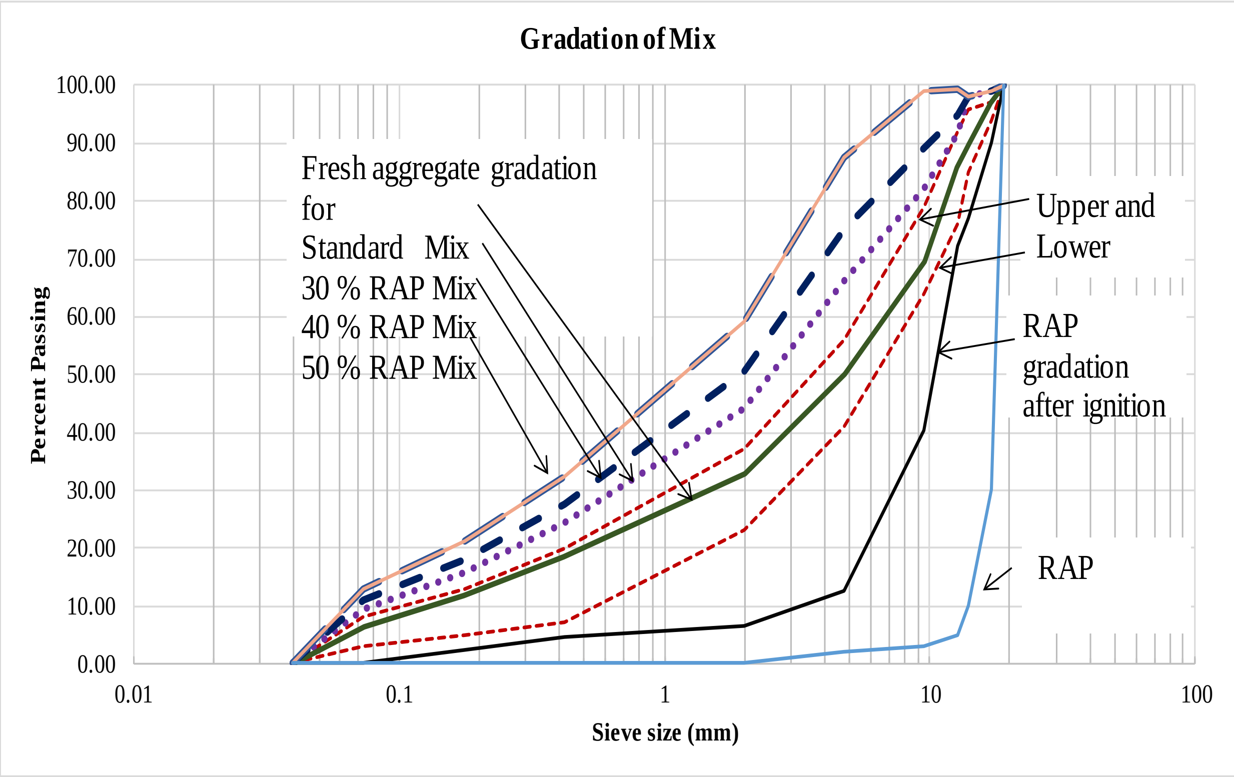


Figure:4.1 Final aggregate blending

4.4 Mix Design and Preparation of Asphalt Mixtures

The Marshall mix design is based on mixture volumetric properties at a specific level of compaction. The resulting volumetric properties from the compaction process are used to select the optimum asphalt content. Marshall mix design provides the optimum asphalt measure based on the Marshall stability and flow test. The results of each test were plotted as percent of asphalt (by total weight of the mix) on a linear scale; the plots are presented in Appendix. Each point shown on the plot is an average of triplicate test specimens. Asphalt contents were determined corresponding to the following:

(a) Maximum Stability.

(b) Maximum Density.

(c) 4 % Air Voids.

The optimum asphalt content of the mix was then calculated as the numerical average of the values of the asphalt contents determined as noted above. For a specific mix type, the optimum asphalt level for all the three rejuvenators found very similar. As the performance of that rejuvenator will be compared among them, so for each mix type asphalt level was kept constant. For example, the optimum asphalt for the mix with 50 % RAP was kept 5 percent for all the rejuvenators. Observing the properties (Appendix) of different mixes, different Marshall criteria of the standard and three RAP mix was concluded in the Table 4.6.

Table 4.6: Summary of Marshall properties

Parameter	Standard	SAE-10 oil			Waste Cooking oil			Waste Engine oil			Specification limit
	0 % RAP mix	30 % RAP mix	40 % RAP mix	50 % RAP mix	30 % RAP mix	40 % RAP mix	50 % RAP mix	30 % RAP mix	40 % RAP mix	50 % RAP mix	
Stability (kg)	1090	1275	1150	1100	1150	1100	970	1120	1200	1100	800 (min)
% air void	4.2	4.35	4	4.2	4.5	3.8	4	4.3	3.95	4.05	4.0 - 6.0
VMA	15.1	16.45	16.2	16.25	16.89	16.5	16.9	16.4	16.7	17.45	14 (min)
Flow (mm)	4.15	3.25	3.75	2.9	3.33	3.75	3.3	3.3	3.5	3.3	2.0 - 4.0
VFA	73	73	75	75	72.5	77	77	72.5	77	77	70-80
% Stability loss	17.77	22.5	15.7	18.6	17.8	10.9	9.8	14.98	9.3	5.02	20 max
Max. Unit weight (gm/cc)	2.288	2.274	2.286	2.275	2.269	2.285	2.281	2.275	2.281	2.271	–
Obtained Optimum asphalt	6.1	5.55	5.15	5.05	5.64	5.13	5.1	5.59	5.17	5.08	–
Used asphalt	6.1	5.5	5.2	5	5.5	5.2	5	5.5	5.2	5	–

The Marshall properties were then determined at optimum asphalt percentage for all mix which can be found in this table. Both the recycled mixture mix were found to satisfy the Marshall design criteria. Stability tests are presented in Table 4.6 as well as the mean of the volumetric properties of the tested specimens. Asphalt contents were kept similar for three different rejuvenators with an air void of 3.8 % to 4.5 % which is within the specification. It can be noticed from the Figure (Appendix) that the air voids decrease with the increase in binder content. The result also demonstrates that after a certain percent of asphalt, the stability of the recycled mixtures decreases due to increase in bitumen content. To determine the stability loss of the modified mixes, Marshall stability analysis was performed for two set of samples. In this process, one set of samples passed the immersion state in water at 60°C for 35 minutes and another set passed the same state for 24 hours. Then the obtained Marshall stability for each set is compared to evince the percent stability loss. It was observed that the use of WCO and WEO reduced the stability loss tremendously for all mixes where SAE-10 oil can even prevent it less significantly. All mixture passes the minimum limit for Marshall stability loss except SAE-10 oil with 50 percent RAP mix, yet the difference is not significant. The results obtained in the present study have shown that WCO and WEO rejuvenated pavement mixtures may be used for road construction.

As illustrated in Table 4.6, all recycled asphalt mixtures provide adequate stability (min. 800 kg. related to wearing course specification). The stability values decrease with increasing of RAP contents for the WCO and SAE-10 oil rejuvenated mixtures. For WEO rejuvenated mix, the stability values increase with the increase in the percentage of RAP up to 40 percent and further increase in the percentage of RAP leads to decrease in stability value. However, no significant variation in the stability values is observed for the mixes above 30% RAP content due to different rejuvenators. As presented in Table 4.6 the flow values decrease with increasing RAP content for the mixtures prepared with all the rejuvenators. This is an indicator of deformation characteristic and the minimum specification limits is 2 mm. Less than this specification implies that the mix is very stiff and brittle. Therefore, observing the Table 4.6 it can be concluded that all the mixture can be accepted as an optimum RAP content based on the specification limits of flow and stability values.

4.5 Evaluation of Asphalt Mixtures

Evaluation of WCO and WEO rejuvenated asphalt mixtures were carried out through different tests. For both waste oils, each test was evaluated through a statistical analysis software Minitab 16. Average value of different tests for different RAP mixes was depicted graphically at three different asphalt levels. The mix with WCO and WEO were evaluated for three different tests as mentioned in Table 3.1. Different characteristics of WCO and WEO rejuvenated RAP were evaluated and those evaluations can be described as below:

4.5.1 Waste Cooking Oil

After determining the optimum asphalt level, three different tests were performed. Different combinations of RAP and rejuvenator were evaluated for three different level of asphalt. Here optimum asphalt level was varied by 0.5 percent below and above. For any asphalt level, three different levels of WCO (13%, 20%, and 27 %) were used. Along with statistical evaluation, the average values were depicted by the graphs. The evaluation of WCO rejuvenated RAP for different tests are mentioned below.

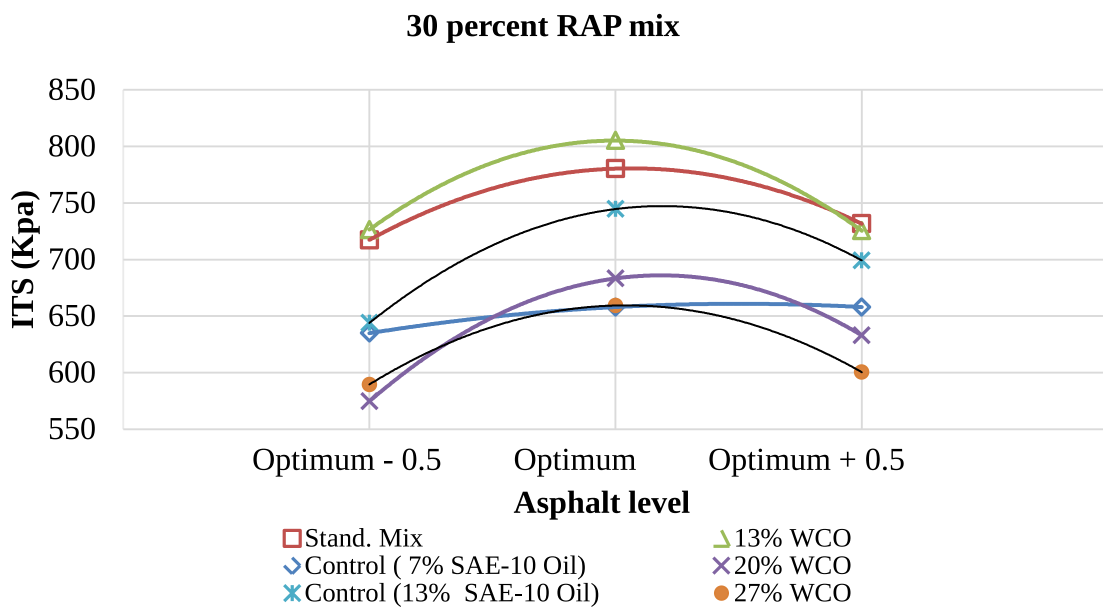
4.5.1.a Indirect Tensile Strength (ITS)

Indirect tensile strength of WCO rejuvenated mixes was evaluated for three different levels of asphalt. ITS value for WCO along with SAE-10 oil and standard mix can be observed in Table 4.7

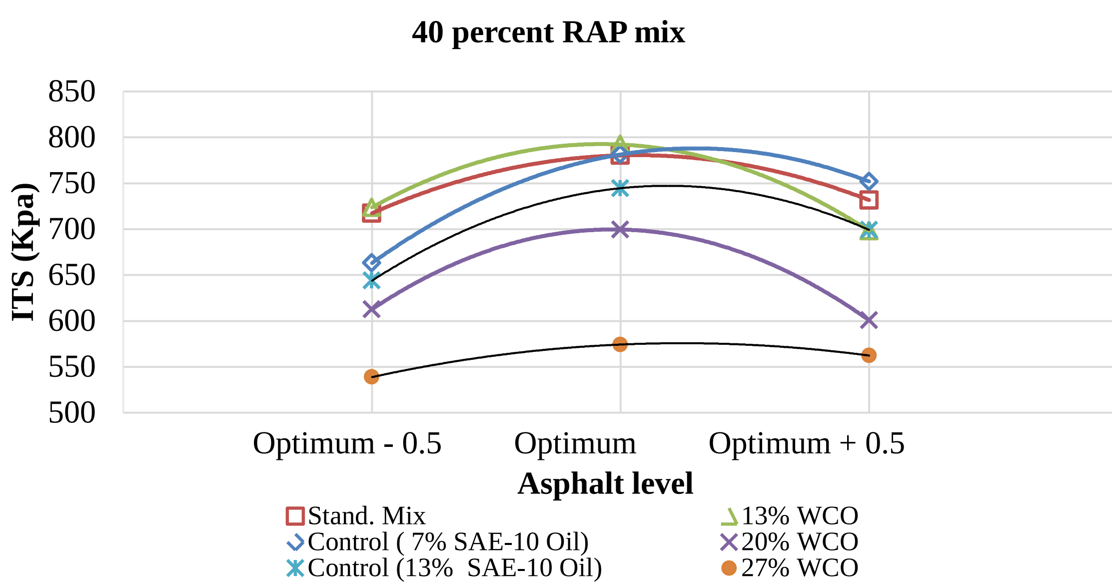
Table 4.7: Summary of indirect tensile strength results for WCO

Mix type	Aspahlt level	Percent of RAP	Percent of rejuvenator	ITS (Kpa)			Avg ITS (Kpa)
				1	2	3	
WCO	op-.5	30	13	728.06	663.06	788.06	726.39
			20	580.57	532.57	610.57	574.57
			27	590.82	529.82	647.82	589.49
	op		13	859.41	789.80	766.20	805.14
			20	737.88	646.65	665.41	683.31
			27	712.30	626.00	639.70	659.33
	op+.5		13	726.78	816.78	632.78	725.45
			20	635.98	723.98	538.98	632.98
			27	599.06	671.06	531.06	600.39
	op-.5	40	13	810.69	784.69	840.69	812.02
			20	745.33	734.33	766.33	748.66
			27	605.48	560.48	646.48	604.14
	op		13	792.56	846.23	903.91	847.57
			20	723.80	783.06	812.32	773.06
			27	698.41	710.18	721.95	710.18
	op+.5		13	799.68	816.68	774.68	797.01
			20	728.23	741.23	721.23	730.23
			27	599.83	620.83	572.83	597.83
	op-.5	50	13	721.35	721.35	728.35	723.69
			20	654.26	651.26	662.26	655.93
			27	539.45	540.45	536.45	538.79
	op		13	765.79	792.20	818.61	792.20
			20	636.68	715.34	764.00	705.34
			27	544.45	582.32	596.19	574.32
	op+.5		13	699.16	724.16	671.16	698.16
			20	674.81	704.81	636.81	672.14
			27	560.27	595.27	531.27	562.27
Control (SAE-10 oil)	op-.5	30	7	636.52	663.52	604.52	634.86
			13	645.20	665.20	621.20	643.87
	op		7	657.30	687.30	629.30	657.96
			13	747.30	764.30	722.30	744.63
	op+.5		7	657.30	687.30	629.30	657.96
			13	697.51	723.51	676.51	699.18
	op-.5	40	7	693.29	735.29	653.29	693.95
			13	599.81	629.81	566.81	598.81
	op		7	785.63	818.63	757.63	787.30
			13	709.60	739.60	685.60	711.60
	op+.5		7	750.38	778.38	720.38	749.71
			13	602.91	624.91	575.91	601.25
	op-.5	50	7	667.08	672.08	650.08	663.08
			13	616.03	631.03	591.03	612.70
	op		7	783.03	787.03	774.03	781.36
			13	695.92	718.92	683.92	699.58
	op+.5		7	749.19	771.19	735.19	751.86
			13	599.64	626.64	575.64	600.64
Standard	op-.5	0	0	740.66	697.66	713.66	717.33
	op			768.72	796.72	775.72	780.38
	op+.5			729.93	697.93	766.93	731.60

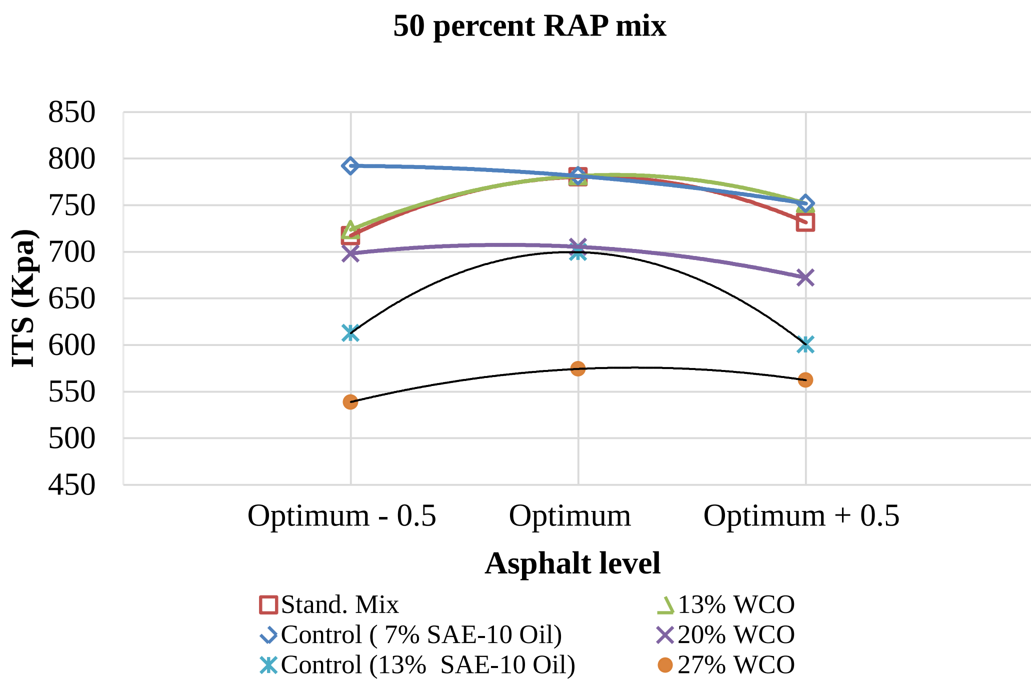
To visualize the effects of asphalt levels on different WCO rejuvenated RAP mixes Figure 4.2 can be observed.



a.



b.



c.

Figure 4.2: Indirect tensile strength of WCO rejuvenated RAP at different asphalt level

a. 30 % RAP mix. b. 40 % RAP mix. c. 50 % RAP mix

Along with WCO rejuvenated mixes, the effect of the standard mix with no RAP and control mixes rejuvenated by SAE-10 oil were also introduced. In most of the cases, WCO asphalt mixtures exhibit higher indirect tensile strength values than the control asphalt mixtures especially with 13 % WCO. The ITS values of WCO rejuvenated samples obtained from this research ranged from 538.79 kpa to 847.57 kpa.

These findings indicated that different levels of oil and asphalt affect the ITS value. ITS value changes due to change in the percentage of RAP in the mix. In most cases, optimum asphalt level showing the maximum ITS value. Not surprisingly, the mixtures with the optimum binder content were found with maximum ITS values, as the changes of asphalt binder content above or below the optimum level resulted in significant ITS reduction. Adding excessive bitumen would affect the aggregate interlocking and hence would affect the ITS of the samples.

ITS results of mixtures involving RAP are higher than the control samples. The greater tensile strength of the mixture containing RAP compared to control mixture also indicates a greater cohesive strength of the RAP. The results also indicate that tensile strength increases as the asphalt content increases and after reaching to a maximum value it starts decreasing. This behavior is because; the tensile strength is related primarily to a function of the binder properties, and its stiffness. The presence of RAP in the mixture makes it stiffer while the addition of asphalt makes it softer.

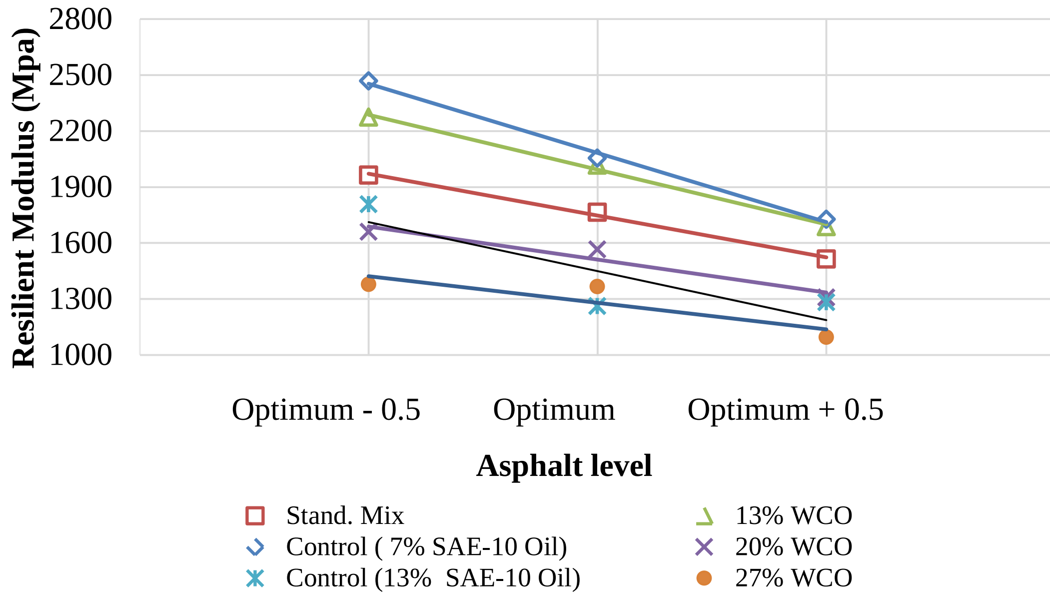
4.5.1.b Modulus of Resilience (M_R)

Modulus of resilience (M_R) of WCO rejuvenated mixes was evaluated for three different levels of asphalt. M_R value for WCO along with SAE-10 oil and the standard mix can be observed in Table 4.8. To visualize the effect of asphalt level on different WCO rejuvenated RAP mixes (Figure 4.3) can be observed. Here the effect of the standard mix with no RAP and control mixes rejuvenated by SAE-10 oil were also introduced. The Figure 4.3 indicates that M_R value decreases with the increasing of asphalt level. This decreasing pattern is almost similar for control and three different levels of WCO. However, the rate of decrease is not same. RAP with 13 percent cooking oil outperformed the control for 40% and 50 % mix. At the same time, the value of 50 percent RAP mixtures exhibits higher M_R values than the other two mixes. A higher percentage of RAP increases the resilience value. The M_R values of WCO rejuvenated samples are ranged from 1095 Mpa to 2652 Mpa. Increasing percentage of oil showed a decrease in the value of resilience.

Table 4.8: Summary of modulus of resilience results for WCO

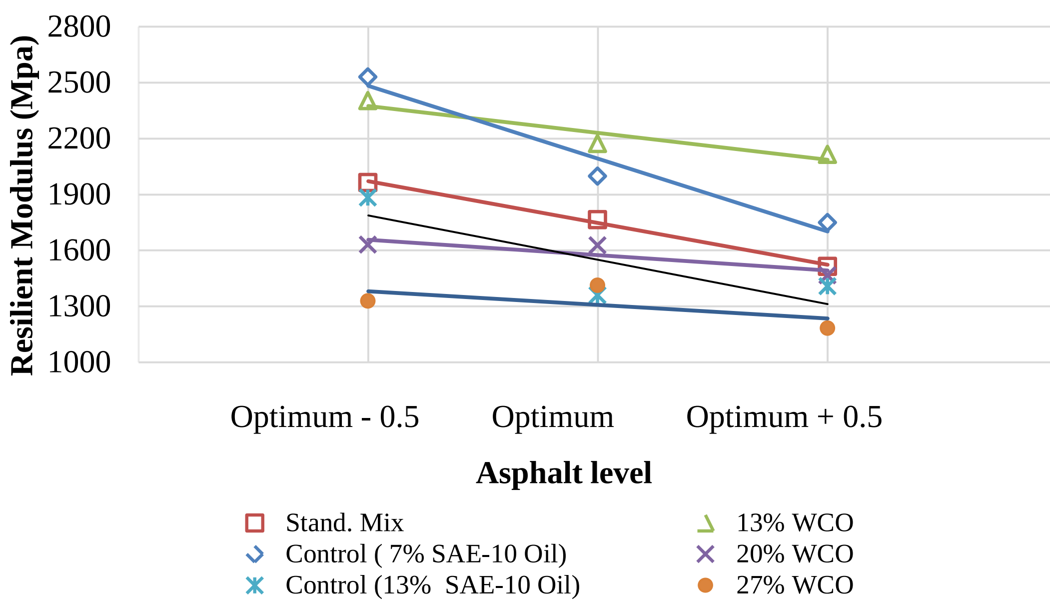
Mix type	Aspahlt level	Percent of RAP	Percent of rejuvenator	Mr (Mpa) 1	Mr (Mpa) 2	Mr (Mpa) 3	Avg Mr (Mpa)
WCO	op-.5	30	13	2281	2408	2136	2275
			20	1647	1792	1542	1660
			27	1382	1477	1277	1379
	op		13	1881	2007	2163	2017
			20	1475	1556	1667	1566
			27	1159	1346	1592	1366
	op+.5		13	1684	1794	1585	1688
			20	1307	1397	1219	1308
			27	1093	1178	1015	1095
	op-.5	40	13	2546	2701	1962	2403
			20	1720	1880	1293	1631
			27	1394	1506	1083	1328
	op		13	2090	2147	2283	2173
			20	1563	1611	1709	1627
			27	1371	1393	1474	1413
	op+.5		13	2112	2257	1972	2114
			20	1458	1593	1347	1466
			27	1173	1293	1083	1183
	op-.5	50	13	2647	2792	2517	2652
			20	1967	2087	1827	1960
			27	1520	1638	1398	1519
	op		13	2099	2220	2360	2227
			20	1765	1810	1924	1833
			27	1423	1466	1558	1482
	op+.5		13	2143	2273	2022	2146
			20	1787	1912	1660	1786
			27	1286	1431	1181	1299
Control (SAE-10 oil)	op-.5	30	7	2469	2619	2314	2467
			13	1810	1940	1670	1807
	op		7	2062	2209	1892	2054
			13	1267	1420	1097	1261
	op+.5		7	1720	1840	1620	1727
			13	1277	1382	1187	1282
	op-.5	40	7	2527	2657	2407	2530
			13	1880	1990	1780	1883
	op		7	1995	2120	1881	1998
			13	1352	1492	1232	1359
	op+.5		7	1750	1875	1620	1748
			13	1400	1527	1297	1408
	op-.5	50	7	2612	2752	2492	2619
			13	1930	2053	1830	1938
	op		7	2195	2345	2053	2198
			13	1584	1712	1451	1583
	op+.5		7	1790	1920	1640	1783
			13	1550	1685	1442	1559
Standard	op-.5	0	0	1859	2050	1980	1963
	op			1688	1858	1750	1765
	op+.5			1581	1436	1526	1514

30 percent RAP mix

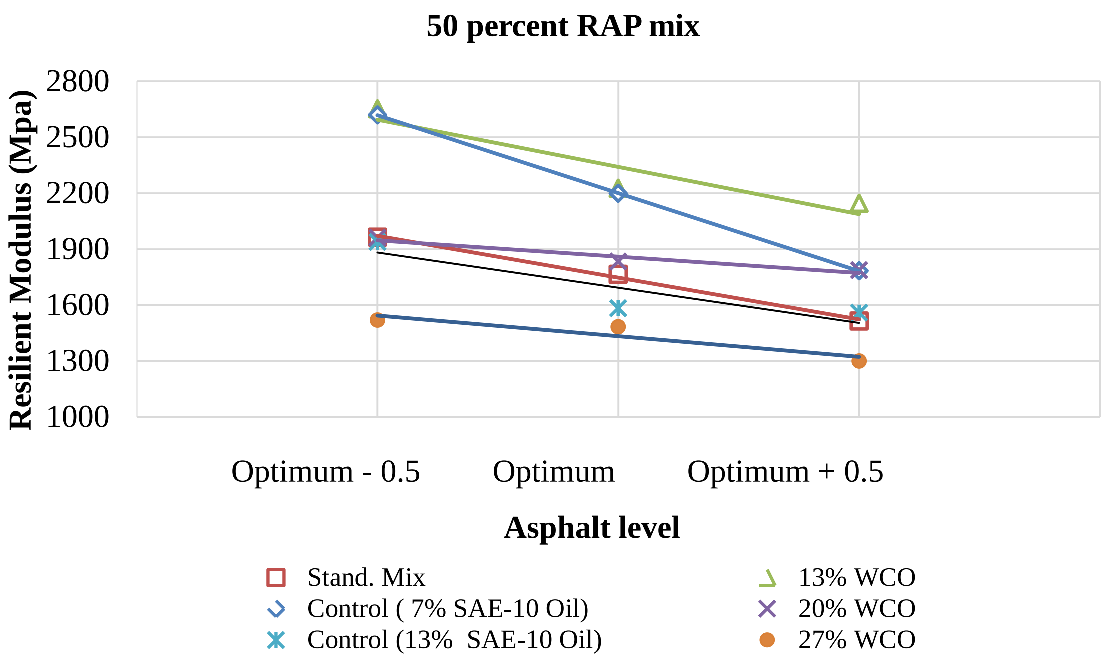


a.

40 percent RAP mix



b.



c.

Figure 4.3: Resilient Modulus of WCO rejuvenated RAP at different asphalt level

a. 30 % RAP mix. b. 40 % RAP mix. c. 50 % RAP mix

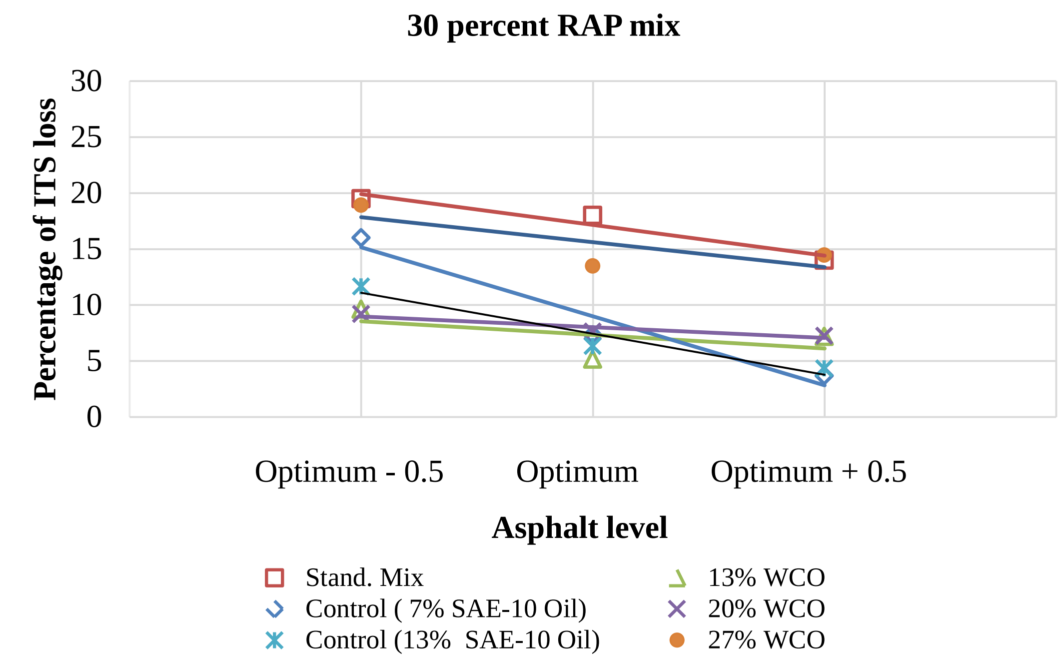
4.5.1.c Durability

The durability test is performed using the Tensile Strength Ratio (TSR) which is applied to investigate durability of samples and to evaluate the influence of WCO on the asphalt mixtures. It should be noted that the increased TSR values or lower percent ITS loss leads to better durability properties, and therefore improves the resistance of asphalt mixtures to moisture influence. The observed value of percent ITS loss for WCO can be found in Table 4.9. To visualize the effect of asphalt level on different WCO rejuvenated RAP mixes Figure 4.4 can be observed. The percentage ITS loss showing inconsistent characteristics due to changes of asphalt level. In most of the cases use of 13 to 20 percent of oil showing similar results. The increment of oil level after 20 percent showed a decrease of resistance to moisture damage.

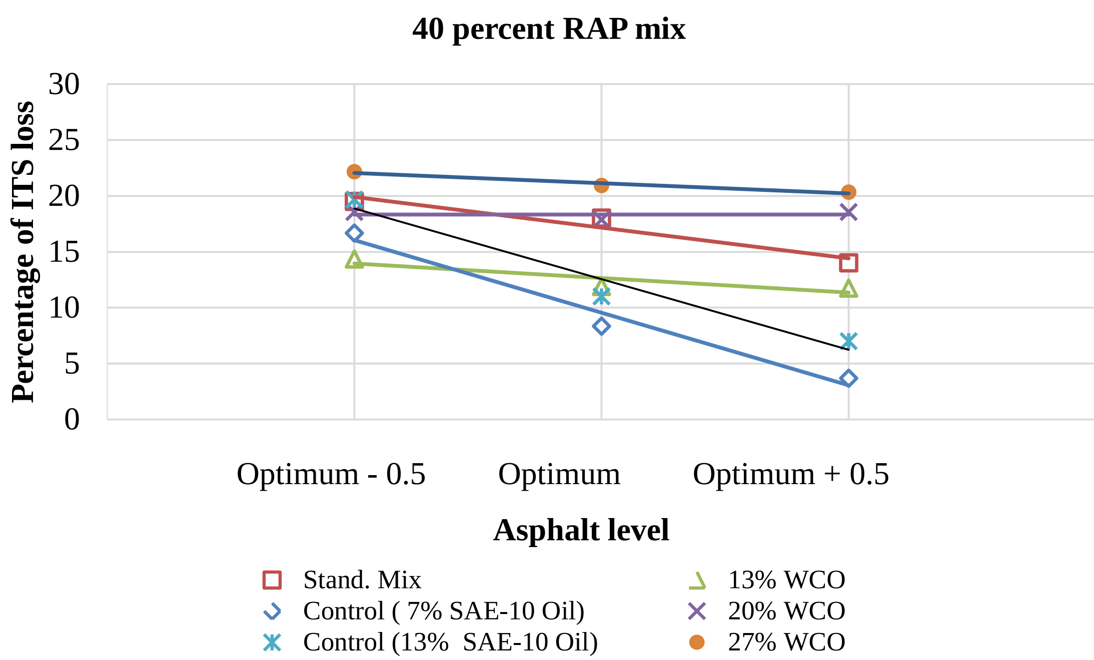
Though 13 percent of WCO always outperformed standard mix, in most of the cases, control is showing better resistance and consistency. Percentage ITS loss values of WCO rejuvenated samples are ranged from 5.17 to 27 percent.

Table 4.9: Summary of percentage its loss results for WCO

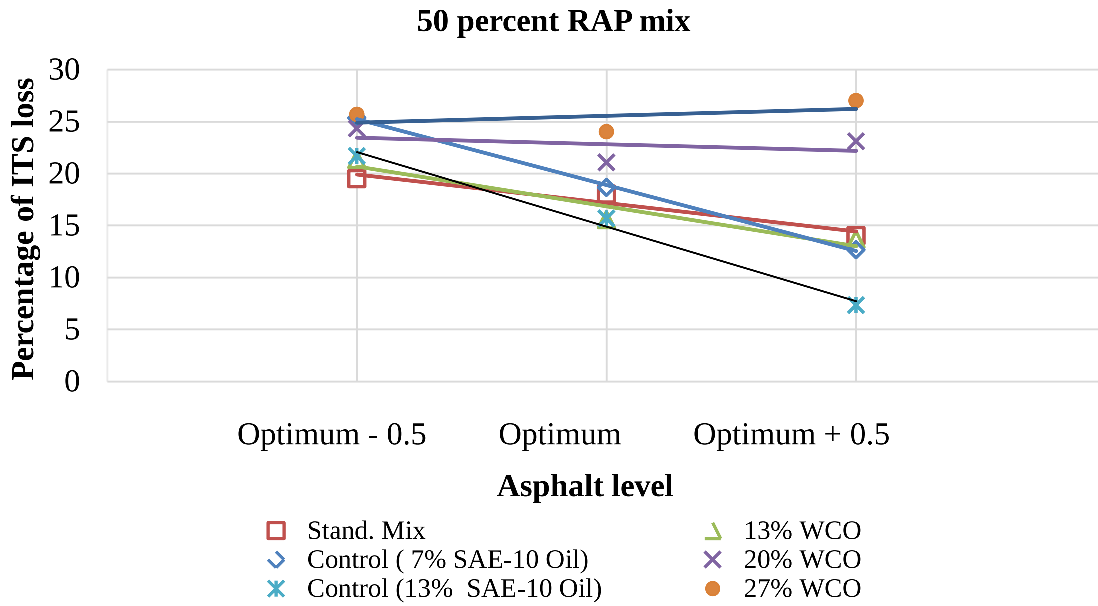
Mix type	Aspahlt level	Percent of RAP	Percent of rejuvenator	Percent ITS loss			Avg percent of ITS loss
				1	2	3	
WCO	op-.5	30	13	9.29	12.29	7.29	9.62
			20	9.03	12.53	6.03	9.19
			27	18.26	22.26	16.26	18.93
	op		13	3.50	5.88	6.14	5.17
			20	7.26	8.40	7.20	7.62
			27	8.66	13.48	18.29	13.48
	op+.5		13	6.85	10.85	3.85	7.19
			20	7.59	10.59	3.59	7.26
			27	14.29	18.79	10.29	14.45
	op-.5	40	13	14.68	16.68	11.68	14.34
			20	19.22	22.22	14.22	18.55
			27	21.49	28.49	16.49	22.16
	op		13	7.71	12.56	15.40	11.89
			20	11.39	19.54	22.69	17.87
			27	16.17	20.92	25.67	20.92
	op+.5		13	11.73	15.73	7.73	11.73
			20	17.55	22.55	15.55	18.55
			27	19.65	24.65	16.65	20.32
	op-.5	50	13	21.00	24.00	19.00	21.33
			20	25.00	27.00	21.00	24.33
			27	26.00	28.00	23.00	25.67
	op		13	9.35	15.21	22.06	15.54
			20	17.04	20.72	25.40	21.06
			27	16.36	23.69	32.03	24.03
	op+.5		13	13.00	17.00	11.00	13.67
			20	22.23	26.00	21.00	23.08
			27	27.00	29.00	25.00	27.00
Control (SAE-10 oil)	op-.5	30	7	16.00	21.00	11.00	16.00
			13	11.00	16.00	8.00	11.67
	op		7	7.00	12.00	3.00	7.33
			13	6.00	11.00	2.00	6.33
	op+.5		7	3.00	7.00	1.00	3.67
			13	4.00	8.00	1.00	4.33
	op-.5	40	7	17.00	20.00	13.00	16.67
			13	19.00	23.00	17.00	19.67
	op		7	9.00	11.00	5.00	8.33
			13	11.00	15.00	7.00	11.00
	op+.5		7	3.00	6.00	2.00	3.67
			13	7.00	9.00	5.00	7.00
	op-.5	50	7	26.00	27.00	23.00	25.33
			13	21.00	21.00	23.00	21.67
	op		7	18.00	22.00	16.00	18.67
			13	16.00	19.00	12.00	15.67
	op+.5		7	13.00	17.00	8.00	12.67
			13	7.00	11.00	4.00	7.33
Standard	op-.5	0	0	19.50	16.70	21.00	19.07
	op			18.00	17.90	15.90	17.27
	op+.5			12.70	16.40	15.80	14.97


30 percent RAP mix
Percentage of ITS loss
30
25
20
15
10
5
0
Optimum - 0.5
Optimum
Optimum + 0.5
Asphalt level
Stand. Mix
Control (7% SAE-10 Oil)
Control (13% SAE-10 Oil)
13% WCO
20% WCO
27% WCO

a.


40 percent RAP mix
Percentage of ITS loss
30
25
20
15
10
5
0
Optimum - 0.5
Optimum
Optimum + 0.5
Asphalt level
Stand. Mix
Control (7% SAE-10 Oil)
Control (13% SAE-10 Oil)
13% WCO
20% WCO
27% WCO

b.



c.

Figure 4.4: ITS Strength loss of WCO rejuvenated RAP at different asphalt level

a. 30 % RAP mix. b. 40 % RAP mix . c. 50 % RAP mix

With the increasing percentage of RAP higher moisture damage is also observed indicating lower moisture resistance capacity of the mix with higher RAP. The mixture with optimum asphalt +/-0.5 was found to be the best in moisture resistance because decreasing the asphalt binder content from this level resulted in the increase of void. The addition of excessive bitumen would affect the aggregate interlocking hence affects the ITS of the samples which reduce the ITS value, however, this changed interlocking due to additional asphalt reduces the air void. So, it may reduce the moisture susceptibility or percent ITS loss.

4.5.2 Waste Engine Oil

After determining the optimum asphalt three different tests were performed. Different combination of RAP and rejuvenator were evaluated for three different level of asphalt. Here optimum asphalt level was verified by +/- 0.5 percent. Along with statistical evaluation, the average value was depicted by the graph. The evaluation of WEO rejuvenated RAP for the different tests are mentioned below.

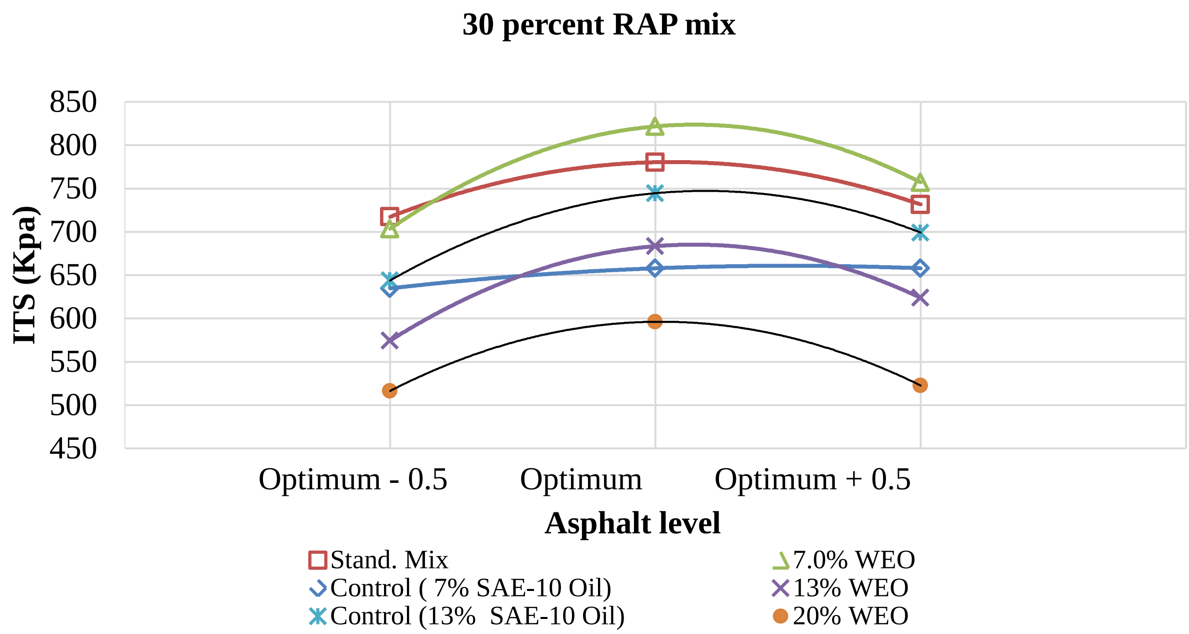
4.5.2.a Indirect Tensile Strength (ITS)

Indirect tensile of WEO rejuvenated mix was evaluated for three different level of asphalt. The observed value of ITS for WEO can be found in Table 4.10.

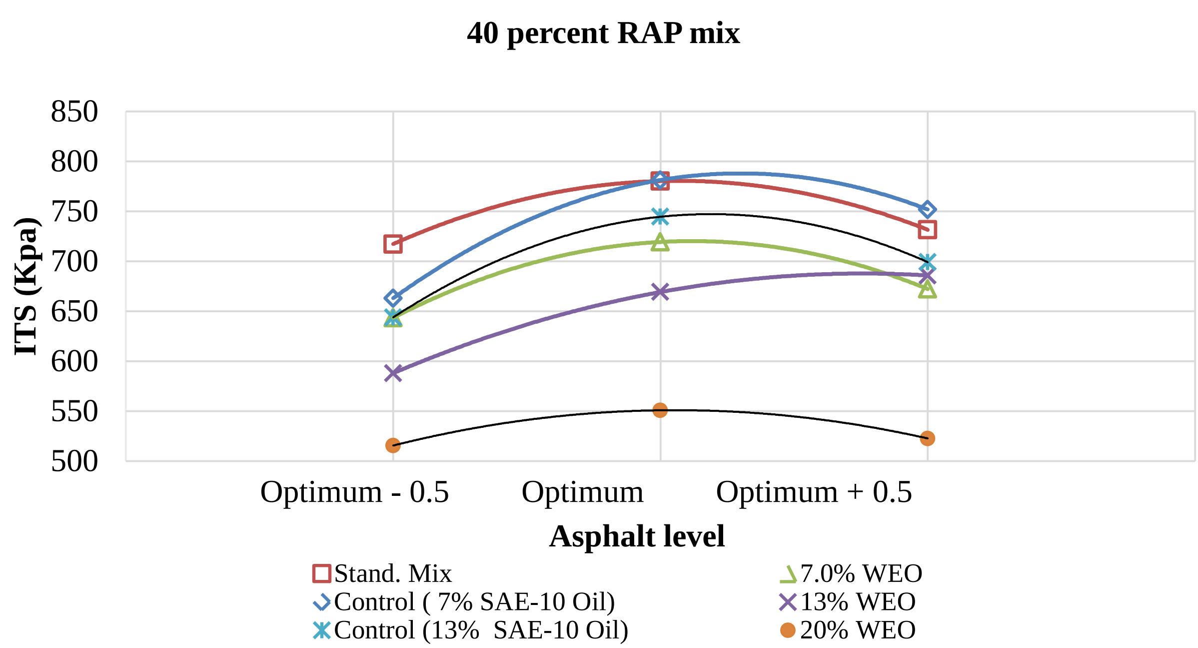
Table 4.10 : Summary of indirect tensile strength results for WEO

Mix type	Aspahlt level	Percent of RAP	Percent of rejuvenator	ITS (Kpa)			Avg ITS (Kpa)
				1	2	3	
WEO	op-.5	30	7	702.81	754.81	652.81	703.48
			13	572.45	604.45	546.45	574.45
			20	519.07	536.07	494.07	516.40
	op		7	799.20	805.07	860.94	821.74
			13	662.20	673.47	714.73	683.47
			20	541.73	610.90	636.08	596.24
	op+.5		7	755.11	798.11	718.11	757.11
			13	625.92	646.92	598.92	623.92
			20	521.05	547.05	500.05	522.71
	op-.5	40	7	645.84	667.84	616.84	643.50
			13	588.72	630.72	544.72	588.06
			20	513.63	546.63	486.63	515.63
	op		7	744.96	762.75	650.54	719.42
			13	695.83	642.62	669.40	669.28
			20	514.09	554.27	584.46	550.94
	op+.5		7	669.28	721.28	626.28	672.28
			13	682.58	743.58	631.58	685.91
			20	525.72	547.72	494.72	522.72
	op-.5	50	7	607.43	630.43	574.43	604.09
			13	578.57	605.57	549.57	577.90
			20	522.62	551.62	499.62	524.62
	op		7	641.03	661.68	612.33	638.35
			13	649.34	658.31	627.29	644.98
			20	514.14	517.20	528.27	519.87
	op+.5		7	662.66	677.66	650.66	663.66
			13	644.53	656.53	627.53	642.87
			20	472.57	483.57	450.57	468.90
Control (SAE-10 oil)	op-.5	30	7	636.52	663.52	604.52	634.86
			13	645.20	665.20	621.20	643.87
	op		7	657.30	687.30	629.30	657.96
			13	747.30	764.30	722.30	744.63
	op+.5		7	657.30	687.30	629.30	657.96
			13	697.51	723.51	676.51	699.18
	op-.5	40	7	693.29	735.29	653.29	693.95
			13	599.81	629.81	566.81	598.81
	op		7	785.63	818.63	757.63	787.30
			13	709.60	739.60	685.60	711.60
	op+.5		7	750.38	778.38	720.38	749.71
			13	602.91	624.91	575.91	601.25
	op-.5	50	7	667.08	672.08	650.08	663.08
			13	616.03	631.03	591.03	612.70
	op		7	783.03	787.03	774.03	781.36
			13	695.92	718.92	683.92	699.58
	op+.5		7	749.19	771.19	735.19	751.86
			13	599.64	626.64	575.64	600.64
Standard	op-.5	0	0	740.66	697.66	713.66	717.33
	op			768.72	796.72	775.72	780.38
	op+.5			729.93	697.93	766.93	731.60

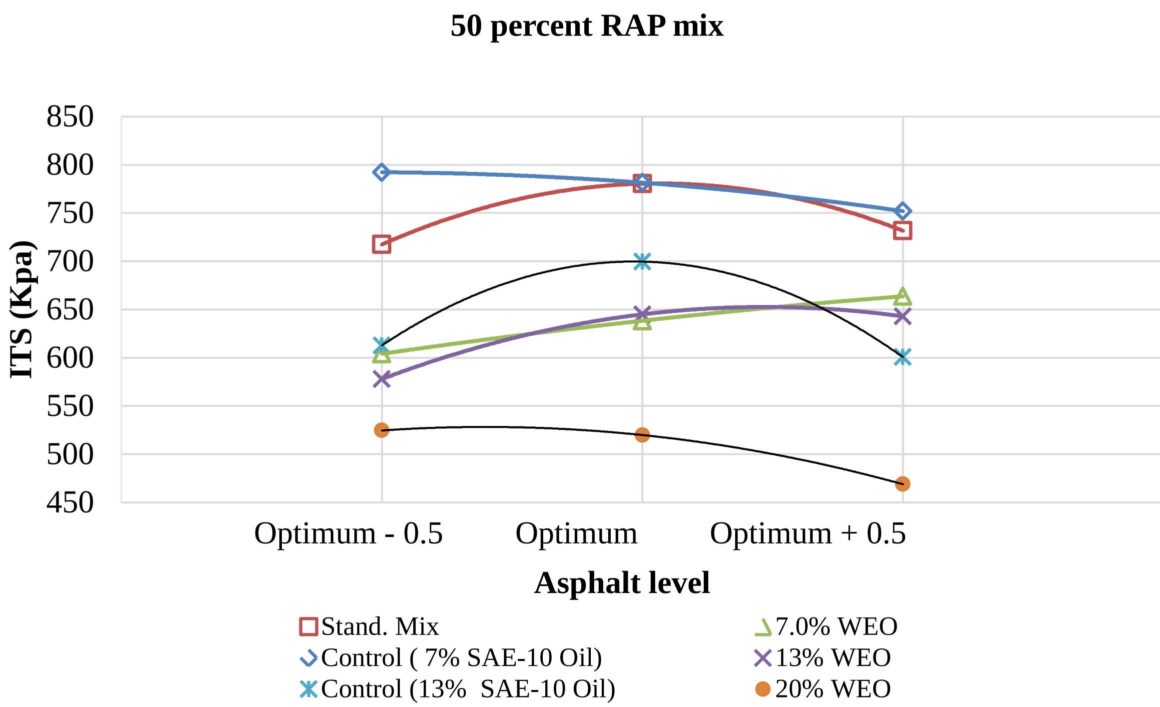
To visualize the effect of asphalt level on different WEO rejuvenated RAP mix Figure 4.5 can be observed.



a.



b



c.

Figure 4.5: Indirect tensile strength of WEO rejuvenated RAP at different asphalt level

a. 30 % RAP mix. b. 40 % RAP mix . c. 50 % RAP mix

Along with WEO, the effect of the standard mix which has no RAP and control mix rejuvenated by SAE-10 oil was also introduced. The WEO asphalt mixtures exhibit higher indirect tensile strength values than the control asphalt mixtures with 7 % WEO for 30 percent RAP, but for other two mixes, it has lower ITS value than control and standard mix. The IDT value decreases with the percentage increase of RAP and asphalt level.

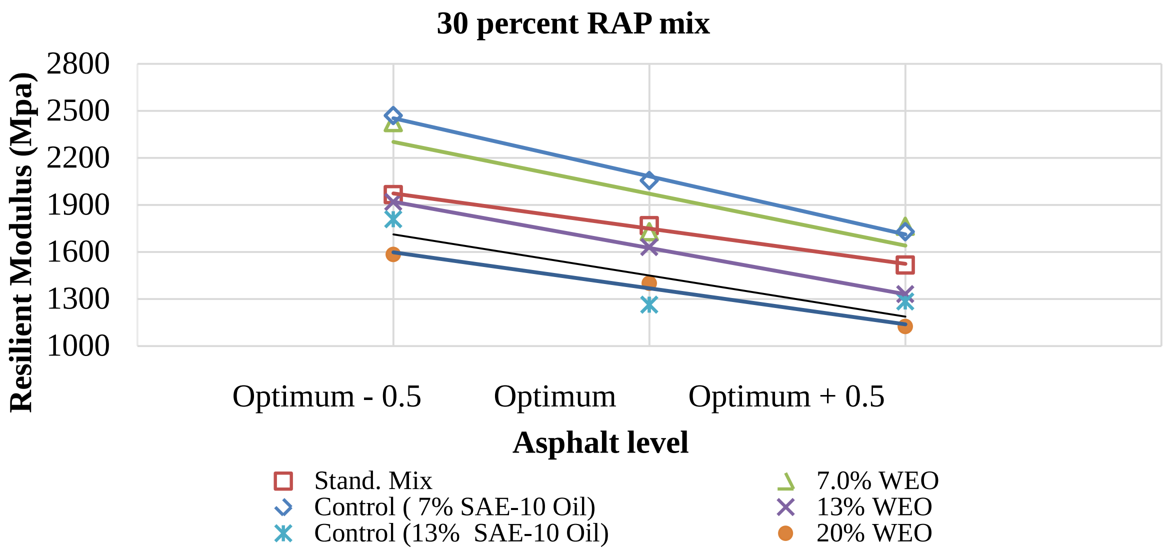
4.5.2.b Modulus of Resilience (M_R)

Modulus of resilience (M_R) strength of WEO rejuvenated mix was evaluated for three different level of asphalt. The observed value of M_R for WEO can be found in Table 4.11.

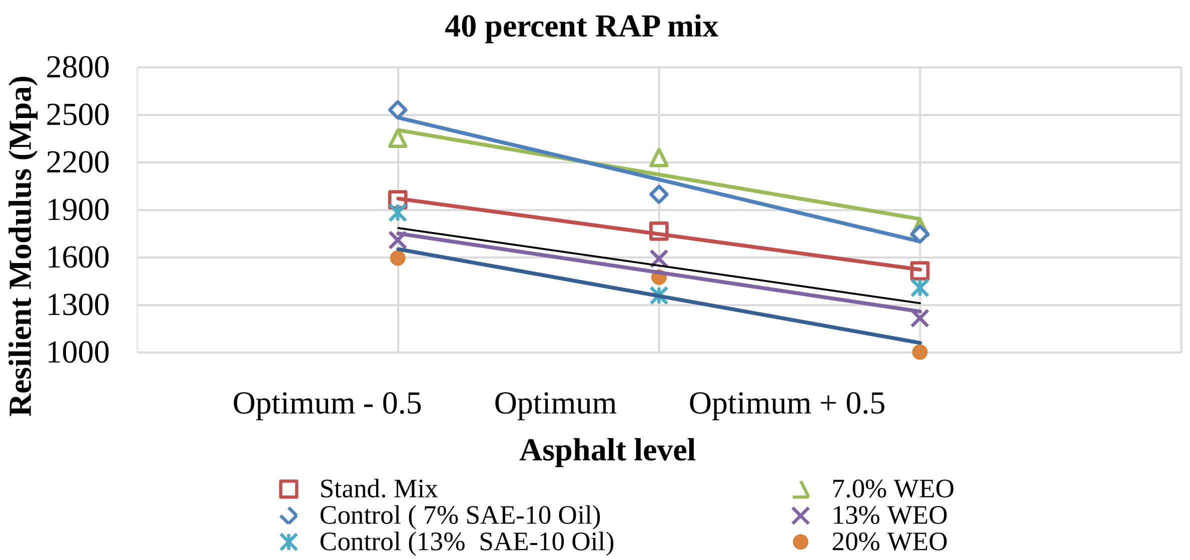
Table 4.11: Summary of modulus of resilience results for WEO

Mix type	Aspahlt level	Percent of RAP	Percent of rejuvenator	Mr (Mpa) 1	Mr (Mpa) 2	Mr (Mpa) 3	Avg Mr (Mpa)
WEO	op-.5	30	7	2422	2542	2307	2424
			13	1921	2051	1781	1918
			20	1577	1688	1479	1581
	op		7	1774	1726	1678	1726
			13	1513	1629	1746	1629
			20	1298	1398	1498	1398
	op+.5		7	1760	1930	1595	1762
			13	1333	1463	1190	1329
			20	1121	1241	1003	1122
	op-.5	40	7	2354	2504	2199	2352
			13	1709	1829	1588	1709
			20	1600	1710	1476	1595
	op		7	2166	2228	2299	2231
			13	1523	1725	1526	1591
			20	1484	1576	1367	1476
	op+.5		7	1789	1909	1674	1791
			13	1220	1331	1100	1217
			20	999	1114	894	1002
	op-.5	50	7	1899	2059	1759	1906
			13	2100	2240	1980	2107
			20	1350	1462	1225	1346
	op		7	1636	1762	1888	1762
			13	1826	1666	1706	1733
			20	1534	1621	1509	1555
	op+.5		7	1620	1772	1480	1624
			13	1700	1840	1575	1705
			20	1333	1443	1215	1330
Control (SAE-10 oil)	op-.5	30	7	2469	2619	2314	2467
			13	1810	1940	1670	1807
	op		7	2062	2209	1892	2054
			13	1267	1420	1097	1261
	op+.5		7	1720	1840	1620	1727
			13	1277	1382	1187	1282
	op-.5	40	7	2527	2657	2407	2530
			13	1880	1990	1780	1883
	op		7	1995	2120	1881	1998
			13	1352	1492	1232	1359
	op+.5		7	1750	1875	1620	1748
			13	1400	1527	1297	1408
	op-.5	50	7	2612	2752	2492	2619
			13	1930	2053	1830	1938
	op		7	2195	2345	2053	2198
			13	1584	1712	1451	1583
	op+.5		7	1790	1920	1640	1783
			13	1550	1685	1442	1559
Standard	op-.5	0	0	1859	2050	1980	1963
	op			1688	1858	1750	1765
	op+.5			1581	1436	1526	1514

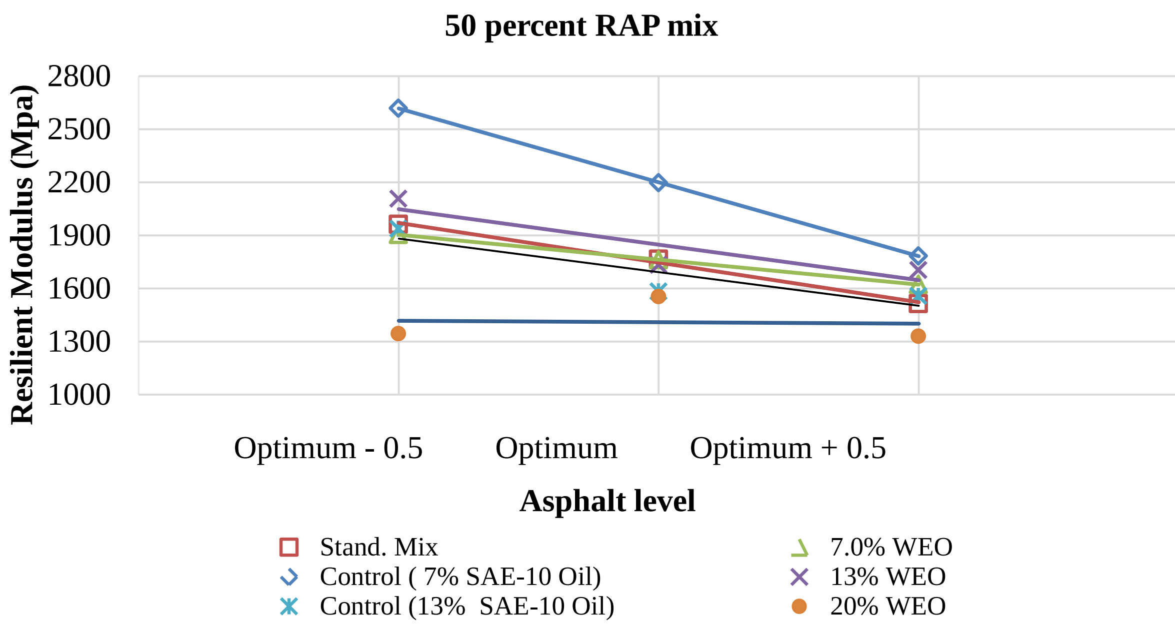
To visualize the effect of asphalt level on different WEO rejuvenated RAP mix Figure 4.6 can be observed. Here the effect of standard mix which has no RAP and control mix rejuvenated by SAE-10 oil was also introduced.



a.



b.



c.

Figure 4.6 : Modulus of resilience of WEO rejuvenated RAP at different asphalt level

a. 30 % RAP mix. b. 40 % RAP mix . c. 50 % RAP mix

M_R value decreases with the increasing of asphalt level. This decreasing pattern is almost similar for control and three different level of WEO. However, the rate of decrease is not same. Only 7 percent of WEO showing similar performance with the control value for a mix till 40 percent. Significant variation in M_R value observed between all level of oil and control value for 50 percent mix. The WEO asphalt mixtures showing lower M_R values than the control mixture but better than the standard mixture. The increasing percentage of asphalt and WEO decrease the M_R for all type of mixes.

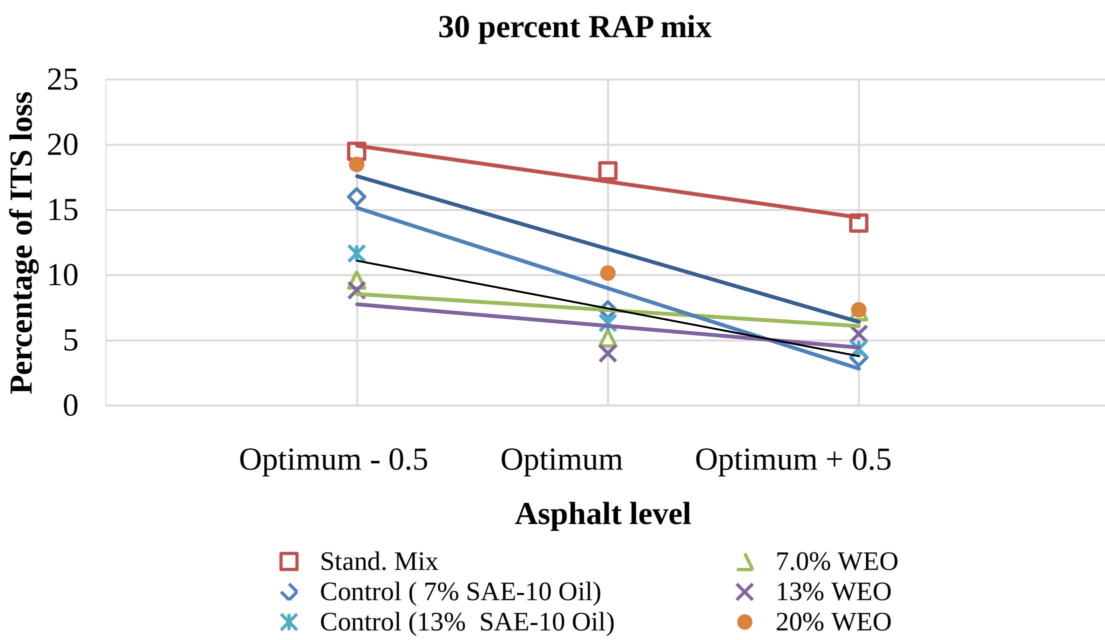
4.5.2.c Durability

The durability test is performed using the Tensile Strength Ratio (TSR) which is applied to investigate durability of samples and to evaluate the influence of WEO on the asphalt mixtures. The observed value of percent ITS loss for WEO can be found in Table 4.12.

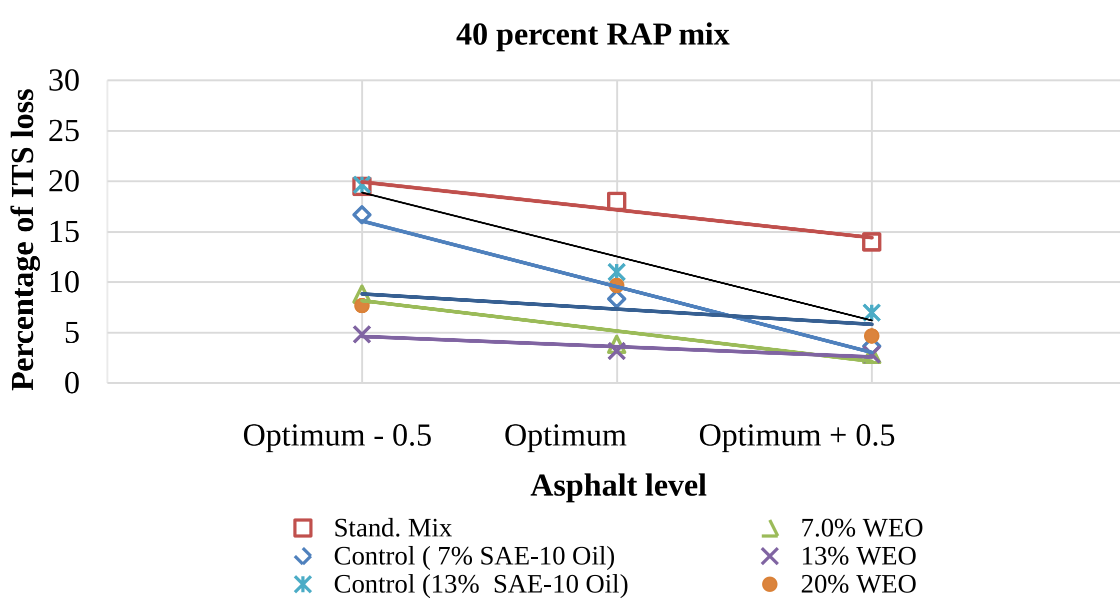
Table 4.12: Summary of percentage its strength loss results for WEO

Mix type	Aspahlt level	Percent of RAP	Percent of rejuvenator	Percent ITS loss			Avg percent of ITS loss
				1	2	3	
WEO	op-.5	30	7	4.00	6.50	2.00	4.17
			13	8.50	11.00	7.00	8.83
			20	18.00	20.50	17.00	18.50
	op		7	4.00	4.00	3.50	3.83
			13	3.20	3.00	5.80	4.00
			20	9.18	10.50	10.82	10.17
	op+.5		7	2.00	4.00	2.00	2.67
			13	5.00	7.00	4.50	5.50
			20	7.00	9.00	6.00	7.33
	op-.5	40	7	9.00	12.00	5.50	8.83
			13	5.00	8.50	1.00	4.83
			20	8.00	10.00	5.00	7.67
	op		7	3.50	5.00	3.00	3.83
			13	2.30	3.00	4.20	3.17
			20	7.00	8.00	14.00	9.67
	op+.5		7	2.00	4.50	2.00	2.83
			13	2.00	4.00	2.50	2.83
			20	4.00	7.00	3.00	4.67
	op-.5	50	7	9.00	11.00	6.00	8.67
			13	14.00	17.00	12.00	14.33
			20	22.00	24.00	20.00	22.00
	op		7	5.00	9.00	13.00	9.00
			13	7.00	11.00	9.00	9.00
			20	16.00	17.00	19.00	17.33
	op+.5		7	7.00	11.00	5.00	7.67
			13	7.00	12.00	4.00	7.67
			20	16.00	21.00	12.50	16.50
Control (SAE-10 oil)	op-.5	30	7	16.00	21.00	11.00	16.00
			13	11.00	16.00	8.00	11.67
	op		7	7.00	12.00	3.00	7.33
			13	6.00	11.00	2.00	6.33
	op+.5		7	3.00	7.00	1.00	3.67
			13	4.00	8.00	1.00	4.33
	op-.5	40	7	17.00	20.00	13.00	16.67
			13	19.00	23.00	17.00	19.67
	op		7	9.00	11.00	5.00	8.33
			13	11.00	15.00	7.00	11.00
	op+.5		7	3.00	6.00	2.00	3.67
			13	7.00	9.00	5.00	7.00
	op-.5	50	7	26.00	27.00	23.00	25.33
			13	21.00	21.00	23.00	21.67
	op		7	18.00	22.00	16.00	18.67
			13	16.00	19.00	12.00	15.67
	op+.5		7	13.00	17.00	8.00	12.67
			13	7.00	11.00	4.00	7.33
Standard	op-.5	0	0	19.50	16.70	21.00	19.07
	op			18.00	17.90	15.90	17.27
	op+.5			12.70	16.40	15.80	14.97

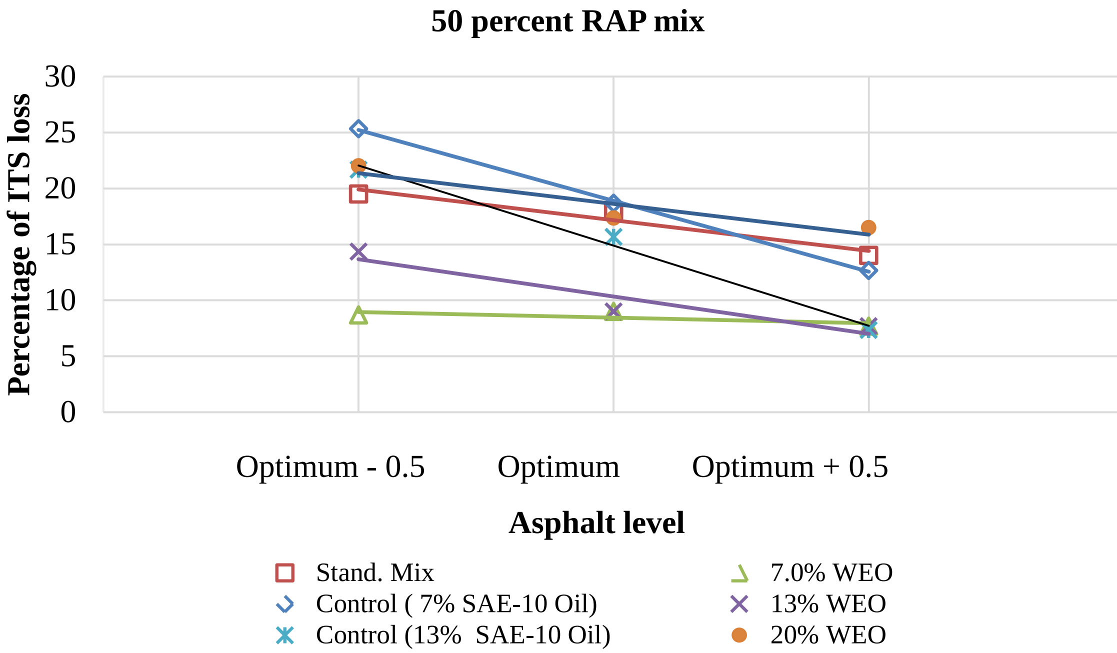
It should be noted that the increased TSR or lower percentage ITS loss values lead to better durability properties, and therefore improve the resistance of asphalt mixtures of moisture influence. To visualize the effect of asphalt level on different WEO rejuvenated RAP mix Figure 4.7 can be observed.



a



b



c

Figure 4.7: ITS strength loss of WEO rejuvenated RAP at different asphalt level

a. 30 % RAP mix. b. 40 % RAP mix . c. 50 % RAP mix

Percentage ITS loss showing inconsistent characteristics due to changes of asphalt level. In most of the cases use of 7 to 13 percent of oil showing similar results. The increment of oil level after 13 percent showed a decrease of resistance to moisture damage which is evinced in Figure 4.7.c. Percentage ITS loss values of WEO rejuvenated samples are ranged from 3.83 to 22 percent.

4.6 Cost Analysis

This section performs a cost analysis to evince the relative comparison of the cost for the mixes with different percent of RAP and rejuvenators. The cost of materials using conventional modification methods with commercial rejuvenators was compared to cost of the mixes rejuvenated by WCO and WEO. In this study only materials cost was considered while in real field other costs such as transport, labor, and processing cost of RAP should be considered.

There is always a fluctuation of material cost around the world. This comparative study used average price during the study period. “Al Yamama Company" was contacted to get the existing price of materials. The price of those materials was also collected from other local construction companies and found almost similar. Based on the prices, average price is taken as the final one. Table 4.13 shows those prices. Following the determination of the optimum asphalt content for each rejuvenator, cost-benefit analysis was performed to inspect the advantages of RAP in terms of economy. The calculation of cost analysis conducted on HMA, and an optimum asphalt content in terms of materials cost is presented in Table 4.13

Table 4.13: Market price of different materials

Material type	Market price ($) per ton
Waste cooking oil	250
Waste engine oil	280
Standard rejuvenator	3100
Bitumen	80
Aggregate	18.5

4.6.1 WCO Rejuvenated Mix

For waste cooking oil rejuvenated mixes, reduces in the final cost is observed. Among the RAP additions, it is clearly observed that utilizing of 30% to 50 % of RAP content with WCO is the most economical in terms of final cost. Little increase in the cost of WCO rejuvenated mixes are observed due to increase in percentage of WCO from 13 to 27 percent. As the cost of WCO is higher than the bitumen, so this increment is observed. However, this increase is not significant. Moreover, WCO rejuvenated mixes outperform the standard mixes as well as standard rejuvenator mixes for any of the used WCO percentage. For 30% WCO rejuvenated mixes, average saving in materials costs are 18.5 and 19.99 percent compare to standard and control mix respectively. For 40 percent RAP mixes this saving is 25.4 percent to 28.6 percent and for 50 percent mixes 32.5 and 36.8 percent compare to standard and control mix respectively. As expected the utilization of RAP decreases the final cost for all cases. However, the similar conclusion cannot be made for SAE-10 oil rejuvenated mixes. It was observed that 13 percent SAE-10 oil rejuvenated mixes are indicating higher materials cost than the standard mixes. As the bitumen costs, very cheap at kingdom compare to this standard rejuvenator, so higher percent of this rejuvenator resulted in higher cost of materials.

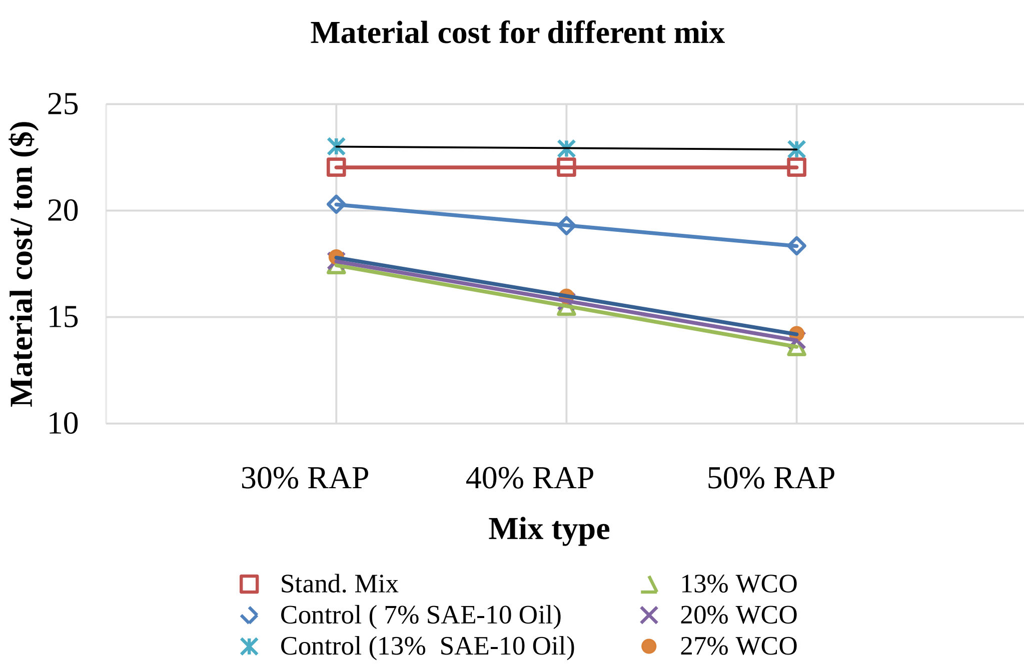


Figure 4.8: Cost of WCO rejuvenated mixes for different percent of RAP

4.6.2 WEO Rejuvenated Mix

The cost of WEO rejuvenated mixes was compared with standard mixes and SAE-10 oil rejuvenated mixes presented in Figure 4.9 shows substantial saving of material cost. For WEO rejuvenated mixes, reduces in the final cost is observed. It is observed that use of RAP content with WEO saves the materials cost. The cost of WEO is little bit higher than the bitumen, so an insignificant increment in total cost is observed due to increase in percentage of WEO from 7 to 20 percent. WEO rejuvenated mixes showing lower materials cost than the standard mixes as well as standard rejuvenator mixes. For 30% WEO rejuvenated mixes, average saving in materials costs are 19.08 and 20.5 percent compare to standard and control mix respectively. For 40 percent RAP mixes this saving is 26.1 percent to 29.3 percent and for 50 percent mixes 33.4 and 37.7 percent compare to standard and control mix respectively. So, the utilization of RAP decreases the final cost for all mixes. However, it was observed that 13 percent of standard mixes are indicating higher materials cost than the standard mixes.

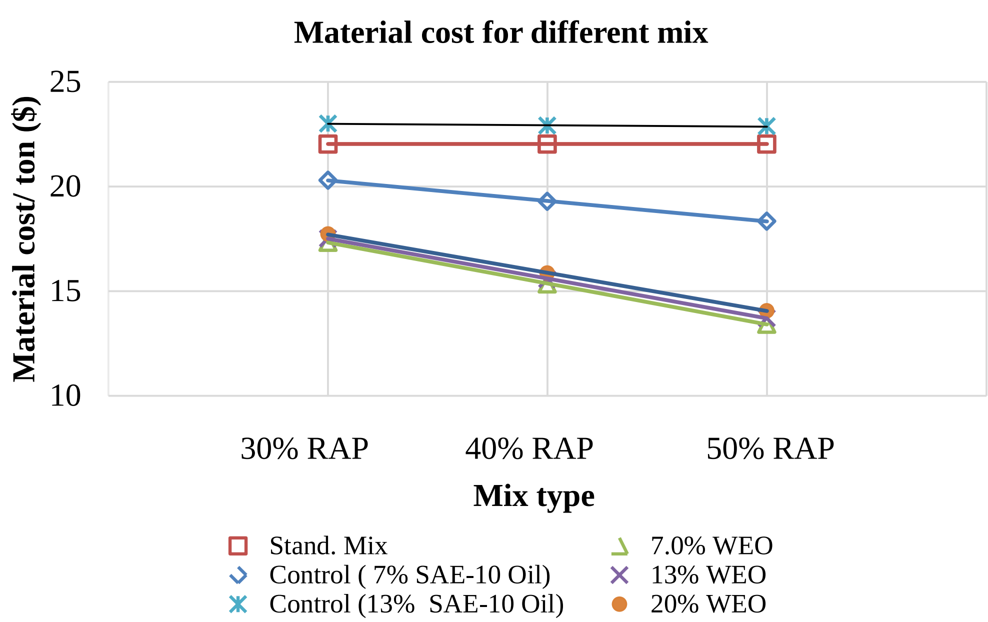


Figure 4.9: Cost of WEO rejuvenated mixes for different percent of RAP

Cost analysis conducted here was concentrated only on the cost of modifier by setting aside the environmental concern. Benefit to eco system and saving waste management cost can be accounted to take decision to choose any alternative solution. Pavement engineers are trying to minimize the required energy for asphalt mixture production for many years. Higher energy requirement in this fields results in higher cost as well as emission of greenhouse gas. Recycling RAP reduces those emissions. Apart from this use of RAP will also reduce the required aggregate in pavement construction. It will save the aggregates and reduce the necessities of quarrying, transportation and the subsequent processing. RAP utilization minimizes the dependency on new petroleum products. So, RAP use can minimize the demand asphalt and subsequent reduction of energy for its refinery process.

4.7 Statistical Analysis of the Asphalt Mixtures Testing

The Statistical test, Analysis of Variances (ANOVA), has been performed to evaluate the influence of different factors on the tested engineering properties of the used asphalt mixtures. Statistical observation of the data was carried out based on null and alternative hypothesis. The null hypothesis (denoted by H_0) is a statement that the value of a population parameter is equal to some claimed value. We test the null hypothesis directly. Either reject H_0 or fail to reject H_0. The alternative hypothesis (denoted by H_a) is the statement that the parameter has a value that somehow differs from the null hypothesis. The null hypothesis is rejected if the P-value is very small, such as 0.05 or less.

Summary of the Statistical analyses is below:

Response variable: ITS , Modulus of resilience, and percent ITS loss

Factors: Asphalt level, mixture type, rejuvenator type and percentage of rejuvenator nested in rejuvenator type.

Percentages of oil for each waste oil are three, whereas for standard rejuvenating agent it is two. For each combination number of replicate is three. To evaluate a specific response (ITS / M_R / % ITS loss) for any of the waste oil compare to control, number of total data point will be 135.

Formulation of theoretical model:

Main effect due to asphalt level in the mix

H_{01} : $\mu_{\text{op-.5}} = \mu_{\text{op}} = \mu_{\text{op-.5}}$

H_{a1} : $\mu_{\text{op-.5}} \neq \mu_{\text{op}} \neq \mu_{\text{op-.5}}$

Main effect due to percentage of RAP in mix

H_{02} : $\mu_{\text{30\% RAP}} = \mu_{\text{40\% RAP}} = \mu_{\text{50\% RAP}}$

H_{a2} : $\mu_{\text{30\% RAP}} \neq \mu_{\text{40\% RAP}} \neq \mu_{\text{50\% RAP}}$

Main effect due to percentage of rejuvenator in mix

H_{03} : $\mu_{\text{13\% WCO}} = \mu_{\text{20\% WCO}} = \mu_{\text{27\% WCO}}$ or $\mu_{\text{7\% WEO}} = \mu_{\text{13\% WEO}} = \mu_{\text{20\% WEO}}$ or $\mu_{\text{7\% SAE-10 oil}} = \mu_{\text{13\% SAE-10 oil}}$

H_{a3} : $\mu_{\text{13\% WCO}} \neq \mu_{\text{20\% WCO}} \neq \mu_{\text{27\% WCO}}$ or $\mu_{\text{7\% WEO}} \neq \mu_{\text{13\% WEO}} \neq \mu_{\text{20\% WEO}}$ or $\mu_{\text{7\% SAE-10 oil}} \neq \mu_{\text{13\% SAE-10 oil}}$

Main effect due to type of rejuvenator in mix

H_{04} : $\mu_{\text{control (SAE-10 oil)}} = \mu_{\text{WCO}} = \mu_{\text{WEO}}$

H_{a4} : $\mu_{\text{control (SAE-10 oil)}} \neq \mu_{\text{WCO}} \neq \mu_{\text{WEO}}$

Interaction effect between factors

H_{05} : Asphalt level has no effect on how percentage of RAP affects mix.

H_{a5} : There is an interaction between asphalt level and percentage of RAP in mix.

H_{06} : Asphalt level has no effect due to different rejuvenator in mix.

H_{a6} : There is an interaction between asphalt level and rejuvenator type in mix.

H_{07} : Percentage of RAP has no effect due to different rejuvenator in mix.

H_{a7} : There is an interaction between percentage of RAP and rejuvenator type in mix.

H_{08} : Asphalt level, percentage of RAP and rejuvenator type have no effect on mix.

H_{a8} : Together asphalt level, percentage of RAP and rejuvenator type affects the mix.

4.7.1 Statistical Analysis of the Asphalt Mixtures Testing for WCO

For three different percentages of WCO and two different percentages of standard rejuvenating agent, three different tests (ITS/ M_R/ % ITS loss) were evaluated. Base on the stated hypothesis, different observed properties of WCO rejuvenated mixes were evaluated which is mentioned below:

4.7.1.a Indirect Tensile Strength (ITS)

Summary of statistical analyses for the ITS value can be observed in Table 4.14.

Table 4.14: ANOVA summary for ITS (WCO)

Factor	P value	Status	Decision	Effect
Asphalt level	0.000	$P < .05$	Reject H_{01}	Significant
Percent of RAP	0.000	$P < .05$	Reject H_{02}	Significant
Percent of Rejuvenator (Rejuv. Type)	0.000	$P < .05$	Reject H_{03}	Significant
Rejuvenator type	0.992	$P > .05$	Can't reject H_{04}	Insignificant
Asphalt level with Percent of RAP	0.880	$P > .05$	Can't reject H_{05}	Insignificant
Asphalt level with Rejuvenator type	0.142	$P > .05$	Can't reject H_{06}	Insignificant
Percent of RAP with Rejuvenator type	0.001	$P < .05$	Reject H_{07}	Significant
Asphalt level, Percent of RAP and Rejuvenator type	0.918	$P > .05$	Can't reject H_{08}	Insignificant

So, the ITS value of the mixes are significantly regulated by asphalt levels, percent of RAP, percent of rejuvenators, and by combine effect of the percent of RAP and rejuvenator type. Whereas rejuvenator type and the interaction effect of asphalt levels with the percent of RAP, asphalt levels with rejuvenator type, and asphalt level, percent of RAP and percent of rejuvenators have an insignificant effect on ITS value of mixes.

The effect of those factors can be evaluated by Tukey's pairwise or Bonferroni's group-wise comparison method. It is observed that optimum asphalt level has a significantly different effect than other two level of asphalt. Optimum asphalt level has a mean ITS value of 734.8 Kpa which higher than other observed ITS mean value of 672.6 kpa and 652.5 kpa for optimum+0.5 and optimum-0.5 level of asphalt respectively. This significant change in ITS value due to shifting from optimum asphalt level supports the observed trend in Figure 4.2. Increasing or decreasing of asphalt level from the optimum asphalt level is affecting the bonding as well as the interlocking of aggregate which subsequently resulting in a decrease of ITS value.

Percent of RAP Mix is significantly affecting the ITS value. 40 percent RAP mix is significantly different from the other two mixes. This mix is showing the highest mean ITS value of 700.8 Kpa. Other two mixes with 30 and 50 percent RAP is showing ITS value of 649.9 Kpa and 646.9 Kpa respectively. This trend is observed in the Figure 4.2. Since RAP aggregate is weaker compared to virgin aggregate, some RAP aggregates could have been crushed during the compaction and resulted in lower ITS value due to increase in the percent of RAP.

ANOVA Table 4.14 indicates that two rejuvenators are not significantly different. It can be evinced further using Tukey's comparison method. WCO rejuvenated mix has a mean ITS value of 686.7 Kpa which is similar to the observed ITS value of 686.6 kpa for the standard rejuvenator SAE-10 oil rejuvenated mix. However, the mixes have different ITS values for different percent of each rejuvenator yet the overall effect of WCO and SAE-10 oil is similar.

ANOVA Table 4.14 also indicates that percentage of rejuvenator has a significant effect. It bolsters the trend in Figure 4.2, where a decreasing trend of ITS value observed due to increase in the percentage of rejuvenator. This is obvious as the increasing percentage of rejuvenator making the asphalt content softer. Further analyses using Tukey's comparison method indicate that percent of rejuvenators are significantly affecting the ITS value. The maximum observed mean ITS value is 769.7 kpa for 13% WCO rejuvenated mixes, where the minimum mean observed ITS value is 604.1 kpa, for 27 % WCO. Group wise comparison following Bonferroni

Method indicates 13% WCO rejuvenated mixes are significantly different from other percentages of rejuvenator.

The significant integration effect between rejuvenator type and percentage of RAP in the mix can be analyzed following Tukey's comparison method. WCO rejuvenated mixes with 40 percent RAP is showing higher ITS value than other mixes. Highest mean ITS value of 735.6 Kpa is observed for WCO rejuvenated mix. This mix is significantly different from other types of mixes. The lowest observed ITS value is 658.1 Kpa for WCO rejuvenated mix. It is also evinced by the group-wise comparison following Bonferroni Method.

4.7.1.b Modulus of Resilience

Summary of statistical analyses for the M_R value can be observed in Table 4.15.

Table 4.15: ANOVA summary for M_R (WCO)

Factor	P value	Status	Decision	Effect
Asphalt level	0.000	$P < .05$	Reject H_{01}	Significant
Percent of RAP	0.000	$P < .05$	Reject H_{02}	Significant
Percent of Rejuvenator (Rejuv. Type)	0.000	$P < .05$	Reject H_{03}	Significant
Rejuvenator type	0.000	$P < .05$	Reject H_{04}	Significant
Asphalt level with Percent of RAP	0.731	$P > .05$	Can't reject H_{05}	Insignificant
Asphalt level with Rejuvenator type	0.000	$P < .05$	Reject H_{06}	Significant
Percent of RAP with Rejuvenator type	0.314	$P > .05$	Can't reject H_{07}	Insignificant
Asphalt level, Percent of RAP and Rejuvenator type	0.334	$P > .05$	Can't reject H_{08}	Insignificant

Modulus of resilience of the mixes is significantly regulated by asphalt level, percent of RAP, percent of rejuvenator, rejuvenator type, and by combine effect of asphalt level with rejuvenator type.Where other interaction effects are found as insignificant on the modulus of resilience value of mix.

The effect of those factors can be evaluated following Tukey's pairwise or Bonferroni's group-wise comparison method. It is observed that the asphalt levels have a significant effect on modulus of resilience value of mix. Optimum-0.5 has the highest mean M_R value of 2037 Mpa where the lower observed mean M_R value of 1575 Mpa is observed for Optimum+0.5 asphalt level. This significant change in M_R value supports the observed trend in Figure 4.3, where lower M_R values were observed due to increase in asphalt level.

Percent of RAP in mixes are significantly affecting the M_R value. Increases in percent of RAP in the mixes have improved the modulus of resilience. Mixes with 50 percent RAP significantly different from the other two mixes and found to be 1912 Mpa. Other two mixes with 40 and 30 percent RAP has 1763 Mpa and 1681 Mpa respectively. It indicates higher M_R value due to increase in the percent of RAP in the mix. So, higher percent of RAP is providing higher stiffness to the mix. The presence of RAP in the pavement leads to increase in stiffness, so higher percent of RAP resulted in increased stiffness of the mixes.

ANOVA Table 4.15 indicates that two rejuvenators are significantly different. It can be evinced by using Tukey's comparison method. WCO rejuvenated mix has a mean M_R value of 1726 Mpa which is lower than the observed M_R value of 1845 Mpa for the standard rejuvenator SAE-10 oil rejuvenated mix.

ANOVA Table 4.15 also indicates that percentage of rejuvenators have a significant effect. The increasing percentage of rejuvenators made the asphalt softer and subsequently resulted in lower stiffness. Further analysis using Tukey's comparison method indicated that different percent of rejuvenators are significantly affecting the M_R. The maximum mean M_R value of 2188 Mpa was observed for 13% WCO rejuvenated mixes where the minimum mean M_R value of 1340 Mpa was observed for 27 % WCO rejuvenated mixes. It also indicated that 13 percent WCO and 7 percent SAE-10 oil have a similar effect on the M_R of mixes. However, 7 percent SAE-10 oil rejuvenated mixes have lower M_R value of 2125 Mpa than the mean M_R value of 13 percent WCO rejuvenated mixes. It also indicated that 20 percent WCO and 13 percent SAE-10 oil have a similar effect on the M_R of mixes, yet 20 percent WCO rejuvenated mixes found to be 1649 Mpa and 13 percent SAE-10 oil rejuvenated mixes found with 1564 Mpa. Tukey's and Bonferroni's pairwise and group-wise comparison respectively indicated that 27 % WCO rejuvenated mixes are significantly different from other percentages of rejuvenators. It can be evinced by observing the Figure 4.3. The graph's trend showed that the use of relatively higher percent of rejuvenator reduces the modulus of resilience.

The significant interaction effect between asphalt level and rejuvenators type can be analyzed following Tukey's comparison method. Mixes with the optimum-0.5 level of asphalt and SAE-10 oil are showing higher M_R value and significantly different from other mixes. Those mixes are showing highest mean M_R value of 2207 Mpa. WCO rejuvenated mixes with the optimum+0.5 level of asphalt is significantly different from other mixes. Mean M_R value of those mixes are 1565 Mpa and those mixes are found with lowest mean M_R values. In Figure 4.3, it can be observed that M_R value decreases due to increase in asphalt from optimum-0.5 level to optimum+ 0.5 levels. This increment in asphalt level made the mixes softer and subsequently resulted in lower M_R. It is also observed that the increasing percent of WCO decrease the M_R value. Increased WCO also made the asphalt less viscous and thus reduced the M_R values. So, it is very likely that the increment in both asphalt level and WCO would result in lower M_R and thus observation supported by Tukey's comparison method. It is also evinced by the group-wise comparison following Bonferroni method that WCO with optimum+0.5 asphalt level significantly differs from other mixes.

4.7.1.c Durability

Summary of statistical analyses for the percentage ITS loss can be observed in Table 4.16.

Table 4.16: ANOVA summary for percent ITS loss (WCO)

Factor	P value	Status	Decision	Effect
Asphalt level	0.000	$P < .05$	Reject H_{01}	Significant
Percent of RAP	0.000	$P < .05$	Reject H_{02}	Significant
Percent of Rejuvenator (Rejuv. Type)	0.000	$P < .05$	Reject H_{03}	Significant
Rejuvenator type	0.000	$P < .05$	Reject H_{04}	Significant
Asphalt level with Percent of RAP	0.873	$P > .05$	Can't reject H_{05}	Insignificant
Asphalt level with Rejuvenator type	0.000	$P < .05$	Reject H_{06}	Significant
Percent of RAP with Rejuvenator type	0.034	$P < .05$	Reject H_{07}	Significant
Asphalt level, Percent of RAP and Rejuvenator type	0.564	$P > .05$	Can't reject H_{08}	Insignificant

So, the percent ITS loss of the mixes are significantly regulated by asphalt level, percent of RAP, percent of rejuvenator, rejuvenator type. It is also regulated by the interaction effect of asphalt level with the percent of RAP and percent of RAP with rejuvenator type. Whereas the interaction effect of asphalt level with the percent of RAP and asphalt level with the percent of rejuvenator and RAP have an insignificant effect on percent ITS loss of mix.

The effect of those factors can be evaluated following Tukey's pairwise or Bonferroni's group-wise comparison method. It is observed that optimum-0.5 asphalt level has a significantly different effect than other two level of asphalt. At this asphalt level a mean percent ITS loss value of 18.368 is observed which higher than other observed mean percent ITS loss value of

13.254 and 11.18 for optimum and optimum +.5 percent of asphalt mix respectively. These significant changes in percent ITS loss value is observed in Figure 4.4.

Percent of RAP mix is significantly affecting the percent ITS loss of mix. Mix with 30 percent RAP has the lower mean percent ITS value of 9.272, where for 40 and 50 percent RAP mix it was 14.213 and 19.317 respectively. Following Tukey's pairwise or Bonferroni group-wise comparison method mix with 30,40 and 50 percent RAP found significantly different from each other. So, higher percentage ITS loss is observed with a higher percentage of RAP in the mix.

ANOVA Table 4.16 indicates that percentage of rejuvenator has a significant effect on percent ITS loss. It can be observed by seeing the trend in Figure 4.4, where a higher percentage loss of ITS value is observed due to increase in the percentage of rejuvenator. Further analyses using Tukey's comparison method indicates how the percent of rejuvenator is significantly affecting ITS. The maximum mean percent ITS loss 20.771 is observed for 27 % WCO rejuvenated mix. Group wise comparison following Bonferroni Method also indicated 27 % WCO rejuvenated mixes are significantly different from other percentages of rejuvenator. Moreover 7 to 13 percent of SAE-oil rejuvenated mixes found with similar effect to the mixes with 13 % WCO.

ANOVA Table 4.16 indicates that two rejuvenators are significantly different. It can be evinced further using Tukey's comparison method. WCO rejuvenated mix has a mean percent ITS loss value of 16.479 which is higher than the observed percent ITS loss value of 12.056 for the SAE-10 oil rejuvenated mix. However, both of the rejuvenators are proving the percentage ITS loss within the maximum allowable loss of 20 percent.

There is a significant interaction effect between the asphalt level and rejuvenator type in the mix. A higher percent of asphalt with any of the rejuvenators found to be less susceptible to moisture damage. It is evinced by the highest percentage ITS loss of 18.5 is for optimum-.5 percent asphalt level rejuvenated by SAE-10 oil. The lowest percent ITS loss observed for optimum+.5 percent asphalt level mix rejuvenated by SAE-10 oil and the mean observed value is 6.444. However, all the WCO rejuvenated mixes have a mean percent ITS loss less than recommended maximum allowable 20 percent.

The significant interaction effect between the rejuvenator type and percentage of RAP in the mix can be analyzed following Tukey's comparison method. A higher percent of RAP with any of the rejuvenators found to be more susceptible to moisture damage. It is evinced by the highest percentage ITS loss of 21.745 for 50 percent RAP mix rejuvenated by WCO. It is significantly different from other mixes. The lowest percent ITS loss observed for 30 percent RAP mix rejuvenated by SAE-10 oil and the mean observed value is 8.222. However, all the WCO rejuvenated mixes have a mean percent ITS loss less than recommended maximum allowable loss except the mixes with 50 percent RAP.

4.7.2 Statistical Analysis of the Asphalt Mixtures Testing for WEO

Base on the stated hypothesis, different observed properties of WEO rejuvenated mix were evaluated which is mentioned below:

4.7.2.a Indirect Tensile Strength (ITS)

Summary of statistical analyses for the ITS value can be observed in Table 4.17. It indicates that ITS value of the mix is significantly regulated by asphalt level, percent of RAP, percent of rejuvenator, and rejuvenator type and by the interaction effect of the percent of RAP with rejuvenator type. Asphalt level with the percent of RAP, asphalt level with rejuvenator type and asphalt level, percent of RAP and rejuvenator type have an insignificant effect on ITS value of mix.

Table 4.17: ANOVA summary for ITS (WEO)

Factor	P value	Status	Decision	Effect
Asphalt level	0.000	P < .05	Reject H_{01}	Significant
Percent of RAP	0.009	P < .05	Reject H_{02}	Significant
Percent of Rejuvenator (Rejuv. Type)	0.000	P < .05	Reject H_{03}	Significant
Rejuvenator type	0.000	P < .05	Reject H_{04}	Significant
Asphalt level with Percent of RAP	0.689	P > .05	Can't reject H_{05}	Insignificant
Asphalt level with Rejuvenator type	0.105	P > .05	Can't reject H_{06}	Insignificant
Percent of RAP with Rejuvenator type	0.009	P < .05	Reject H_{07}	Significant
Asphalt level, Percent of RAP and Rejuvenator type	0.402	P > .05	Can't reject H_{08}	Insignificant

The effect of those factors can be evaluated following Tukey's pairwise or Bonferroni's group-wise comparison method. It is observed that optimum asphalt level has significantly different effect than other two level of asphalt. Optimum asphalt level has a mean ITS value of 695.6 Kpa which is higher than other observed ITS mean value of 647.3 kpa and 612.2 kpa for higher and lower level of asphalt respectively. This significant change in ITS value due to shifting from optimum asphalt level supports the observed trend in Figure 4.5.

Percent of RAP mix is significantly affecting the ITS value. ITS value found to be decreasing with the percentage increasing of RAP in the mix. Tukey's comparison method indicates that mix with 30 and 40 percent, RAP has a similar effect on ITS value, yet the mean ITS value for 40 percent RAP mix is 654.5 Kpa which is smaller than the observed mean ITS value of 664.5 kpa for 30 percent RAP mix. 30 percent RAP mix is significantly different from 50 percent mix. The observed mean ITS value is 636.1 kpa for 50 percent RAP mix and less than the observed

ITS value for 30 percent mixes. So, a decreasing trend in ITS value observed due to increase in percentage of RAP in the mixes.

ANOVA Table 4.17 also indicates that the percentage of rejuvenators have a significant effect. It supports the trend in Figure 4.5 where a decreasing trend of ITS value observed due to increase in the percentage of rejuvenator. This is obvious as the increasing percentage of rejuvenator making the asphalt content softer. Further analyses using Tukey's comparison method indicate that percent of rejuvenator is significantly affecting ITS. The maximum mean ITS value of 716.3 kpa is observed for 7% SAE-10 oil whereas the minimum mean ITS value observed for 20 % WEO is 526.4 Kpa. It is also supported by a group-wise comparison following Bonferroni method and indicated that 20% WEO rejuvenated mixes are significantly different from other percentages of rejuvenator. Those observations bolstered the decreasing trend in ITS value due to increase in percentage of rejuvenators in Figure 4.5.

ANOVA Table 4.17 indicates that two rejuvenators are significantly different. It can be evinced further using Tukey's comparison method. WEO rejuvenated has a mean ITS value of 616.8 Kpa, which is smaller than the observed ITS value of 686.6 Kpa for the standard rejuvenator SAE-10 oil rejuvenated mix.

The significant integration effect between rejuvenator type and percentage of RAP in the mix can be analyzed following Tukey's comparison method. Highest mean ITS value of 690.4 Kpa is observed for SAE-10 oil rejuvenated mix. This mix is significantly different from other WEO rejuvenated mixes. WEO rejuvenated mixes with 30 percent RAP are showing a mean ITS value of 644.4 kpa which is the highest ITS value among all WEO rejuvenated mixes. The lowest observed ITS value is 587.2 Kpa for WEO rejuvenated mix. It is also evinced by the group-wise comparison following Bonferroni Method.

4.7.2.b Modulus of Resilience

Summary of statistical analyses for the M_R value can be observed in Table 4.18.

Table 4.18: ANOVA summary for M_R (WEO)

Factor	P value	Status	Decision	Effect
Asphalt level	0.000	$P < .05$	Reject H_{01}	Significant
Percent of RAP	0.026	$P < .05$	Reject H_{02}	Significant
Percent of Rejuvenator (Rejuv. Type)	0.000	$P < .05$	Reject H_{03}	Significant
Rejuvenator type	0.000	$P < .05$	Reject H_{04}	Significant
Asphalt level with Percent of RAP	0.139	$P > .05$	Can't reject H_{05}	Insignificant
Asphalt level with Rejuvenator type	0.003	$P < .05$	Reject H_{06}	Significant
Percent of RAP with Rejuvenator type	0.092	$P > .05$	Can't reject H_{07}	Insignificant
Asphalt level, Percent of RAP and Rejuvenator type	0.092	$P > .05$	Can't reject H_{08}	Insignificant

Modulus of resilience value of the mix is significantly regulated by asphalt level, percent of RAP, percent of rejuvenator, rejuvenator type and by the combine effect of asphalt level with rejuvenator type. Whereas the combine effect of asphalt level with percent of RAP, percent of RAP with rejuvenator type, and asphalt level, percent of RAP and rejuvenator type are found with insignificant effect on modulus of resilience value of mix.

The effect of those factors can be evaluated following Tukey's pairwise or Bonferroni's group wise comparison method. It is observed that the asphalt level has significant effect on modulus of resilience value of mix. Optimum-0.5 has the highest mean M_R value of 2045 Mpa whereas the lowest mean M_R value of 1508 Mpa is observed for optimum+ 0.5 asphalt levels. This significant change in M_R value supports the observed trend in Figure 4.6 where lower M_R value is observed for an increase in asphalt level.

ANOVA table also indicates that percentage of RAP has significant effect. The maximum mean M_R value of 1810 Mpa is observed for 50 percent RAP mix where the minimum mean M_R value is 1710 Mpa for 30 percent RAP mixes. Those two mixes are significantly different from each other. Mixes with 40 percent RAP found with a mean M_R value of 1742 Mpa. So, an increasing in M_R value is observed due to increase in percent of RAP, which is an indication of stiffer mix due to presence of RAP.

ANOVA Table 4.18 also indicates that percentage of rejuvenator has significant effect. It can be evinced by observing the Figure 4.6 where a decreasing trend of M_R value observed due to increase in percentage of rejuvenator. This is due to the increasing percentage of rejuvenator making the asphalt content softer. Further analyses using Tukey's comparison method indicate that percent of rejuvenator is significantly affecting M_R. The maximum mean M_R value 2125 Mpa is observed for 7% SAE-10 oil. Group wise comparison following Bonferroni Method indicates 7 % SAE-10 oil significantly different from other percentages of rejuvenator. 7 to 13 percent WEO and 13 percent SAE-10 oil rejuvenated mixes were found with similar effect. The minimum mean M_R value of 1378 Mpa is observed for 20 % WEO and significantly different from other mixes.

ANOVA Table 4.18 indicates that two rejuvenators are significantly different. WEO rejuvenated has a mean M_R value 1664 Mpa which is lower than the observed M_R value 1845 Mpa for the standard rejuvenator SAE-10 oil rejuvenated mix. Following Tukey's or Bonferroni comparison method it can be observed that they are significantly different from each other.

The significant integration effect between rejuvenator type and percentage of RAP in the mix can be analyzed following Tukey's comparison method. SAE-10 oil rejuvenated mixes are showing higher M_R value than any of WEO rejuvenated mixes. Highest mean M_R value of 1947 Mpa is observed for SAE-10 oil rejuvenated 50 percent RAP mix whereas the lowest M_R value of 1654 Mpa is observed for WEO rejuvenated 30 percent RAP mix. However, 50 percent WEO rejuvenated mixes with a mean M_R value of 1674 Mpa found with similar effect to the SAE-10 oil rejuvenated mixes.

4.7.2.c Durability

Summary of statistical analyses for the percentage ITS loss can be observed in Table 4.19.

Table 4.19: ANOVA summary for percent ITS loss (WEO)

Factor	P value	Status	Decision	Effect
Asphalt level	0.000	$P < .05$	Reject H_{01}	Significant
Percent of RAP	0.000	$P < .05$	Reject H_{02}	Significant
Percent of Rejuvenator (Rejuv. Type)	0.000	$P < .05$	Reject H_{03}	Significant
Rejuvenator type	0.000	$P < .05$	Reject H_{04}	Significant
Asphalt level with Percent of RAP	0.763	$P > .05$	Can't reject H_{05}	Insignificant
Asphalt level with Rejuvenator type	0.000	$P < .05$	Reject H_{06}	Significant
Percent of RAP with Rejuvenator type	0.004	$P < .05$	Reject H_{07}	Significant
Asphalt level, Percent of RAP and Rejuvenator type	0.413	$P > .05$	Can't reject H_{08}	Insignificant

So, the percent ITS loss of the mixes are significantly regulated by asphalt level, percent of RAP, percent of rejuvenator, rejuvenator type. It is also regulated by the interaction effect of asphalt level with rejuvenator type and percent of RAP with rejuvenator type. The interaction effect of asphalt level with the percent of RAP and asphalt level with the percent of RAP with rejuvenator type have no effect on the ITS loss of mix.

The effect of those factors can be evaluated following Tukey's pairwise or Bonferroni's group-wise comparison method. It is observed that optimum-0.5 asphalt level has a mean 14.685 percent ITS loss which higher than other observed mean percent ITS loss value of 9.5 and 6.426 for optimum and optimum +.5 percent of asphalt mix respectively. These significant changes in percent ITS loss value is observed in Figure 4.7 where higher percent of asphalt decreases the percent ITS loss. The increased percent of asphalt reduces the air void in the mix and thus hinders the intrusion of water in the mix and may reduce the percent ITS loss due to moisture.
Percent of RAP in mixes are significantly affecting the percent ITS loss values. Mixes with 50 percent RAP has the highest mean percent ITS loss value of 14.676. Those mixes with 50 percent RAP are significantly different from other mixes. The mixes with 30 and 40 percent RAP have a mean percent ITS loss of 8.213 and 7.722 respectively. Following Tukey's pairwise or Bonferroni group-wise comparison method it can be concluded that all the mixes have a lower percentage ITS loss than the maximum allowable loss. However, an increasing trend in percent ITS loss is observed due to increase in percent of RAP in the mixes.

ANOVA Table 4.19 indicates that percentage of rejuvenator has a significant effect on percent ITS loss. It can be observed by seeing the trend in Figure 4.7 where a higher percentage loss of ITS value is observed due to increase in the percentage of rejuvenator. Further analyses using Tukey's comparison method indicates how the percent of rejuvenator is significantly affecting percent ITS loss. The maximum mean percent ITS loss of 12.648 is observed for 20 % WEO rejuvenated mix. The lowest observed loss is 5.722 percent for 7 percent WEO rejuvenated mix. Group wise comparison following Bonferroni method also indicated that the mixes rejuvenated by 7 to 13 percent of WEO are significantly different from other mixes. However, all the mixes are showing an ITS loss within the allowable maximum limit.

ANOVA Table 4.19 indicates that two rejuvenators are significantly different. It can be evinced further using Tukey's comparison method. WEO rejuvenated mix has a mean percent ITS loss value of 8.352 which is significantly smaller than the observed percent ITS loss value of 12.056 for the SAE-10 oil rejuvenated mix. Both are within the specified limit.

There is a significant integration effect between the asphalt level and rejuvenator type in the mix. A higher percent of asphalt with any of the rejuvenators found to be less susceptible to moisture damage. It is evinced by the highest percentage ITS loss of 18.5 is for optimum-.5 percent asphalt level rejuvenated by SAE-10 oil. The lowest percent ITS loss observed for optimum+.5 percent asphalt level mix rejuvenated by WEO oil and the mean observed value is 6.407. However, all WCO rejuvenated mix has a mean percent ITS loss less than recommended maximum allowable 20 percent.

The significant interaction effect between the rejuvenator type and percentage of RAP in the mix can be analyzed following Tukey's comparison method. A higher percent of RAP with any of the rejuvenators found to be more susceptible to moisture damage. It is evinced by the highest percentage ITS loss of 16.889 for the SAE-10 oil rejuvenated 50 percent RAP mixes. It is significantly different from other mixes. The lowest percent ITS loss observed for 40 percent RAP mix rejuvenated by WEO and the mean observed value is 5.37. However, the observed percent losses for all WEO rejuvenated mixes are within the recommended maximum allowable value.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The following conclusions can be drawn from this study.

5.1.1 Waste Cooking Oil

WCO asphalt mixtures exhibit higher indirect tensile strength values than the control asphalt mixtures especially with 13 % WCO. The ITS values of tested samples obtained from this research ranged from 660 kpa to 850 kpa. The M_R values of WCO rejuvenated samples are ranged from 1365 Mpa to 2226 Mpa. Increasing percentage of oil showed a decrease in the value of resilience. In most of the cases use of 13 to 20 percent of oil showing similar results. The increment of oil level after 20 percent showed a decrease of resistance to moisture damage. Percentage ITS loss values of WCO rejuvenated samples are ranged from 5 to 24 percent. Use of 30 to 50 percent WCO rejuvenated mixes, can save 18.5 to 32.5 percent of materials cost compare to traditional mixes where it is 19.99 to 36.8 percent economical compare to SAE-10 oil rejuvenated mixes. So, the conclusions for WCO rejuvenated mixes can stated as below:

1. WCO rejuvenated mix has a mean ITS value of 686.7 Kpa which is similar to the observed ITS value of 686.6 kpa for the standard rejuvenator SAE-10 oil rejuvenated mix. The maximum observed mean ITS value is 769.7 kpa for 13% WCO, whereas the minimum mean ITS value of 604.1 kpa is observed for 27 % WCO.

2. WCO rejuvenated mixes with 40 percent RAP is showing higher ITS value than other mixes. Highest mean ITS value of 735.6 Kpa is observed for WCO rejuvenated mix. The lowest observed ITS value is 658.1 Kpa for WCO rejuvenated mix.
3. For modulus of resilience, the mixes with 50 percent RAP are significantly different from the other two mixes and found to be 1912 Mpa. Other two mixes with 40 and 30 percent RAP have a M_R value of 1763 Mpa and 1681 Mpa respectively. It indicates higher M_R value due to increase in the percent of RAP in the mix.
4. The maximum mean M_R value of 2188 Mpa was observed for 13% WCO rejuvenated mixes whereas the minimum mean M_R value of 1340 Mpa was observed for 27 % WCO rejuvenated mixes. 13 percent WCO and 7 percent SAE-10 oil have a similar effect on the M_R of mixes.
5. Mix with 30 percent RAP has the lower mean percent ITS value of 9.272, whereas for 40 and 50 percent RAP mix it was 14.213 and 19.317 respectively. So, higher percentage ITS loss is observed with a higher percentage of RAP in the mix.
6. The maximum mean percent ITS loss observed value is 20.771 for 27 % WCO rejuvenated mix. Moreover 7 to 13 percent SAE-oil rejuvenated mixes found with similar effect to the mixes with 13 % WCO rejuvenated mixes.
7. WCO rejuvenated mix has a mean percent ITS loss value of 16.479 which is higher than the observed percent ITS loss value of 12.056 for the SAE-10 oil rejuvenated mix. However, both of the rejuvenators are proving the percentage ITS loss within the maximum allowable loss of 20 percent.
8. Highest percentage ITS loss of 21.745 for 50 percent RAP mix rejuvenated by WCO. It is significantly different from other mixes. The lowest percent ITS loss observed for 30

percent RAP mix rejuvenated by SAE-10 oil and the mean observed value is 8.222. However, all of the WCO rejuvenated mixes have a mean percent ITS loss less than recommended maximum allowable loss except the mixes with 50 percent RAP.

5.1.2 Waste Engine Oil

The WEO asphalt mixtures exhibit higher indirect tensile strength values than the control asphalt mixtures with 7 % WEO for 30 percent RAP, but for other two mixes, it has lower ITS value than the control and standard mixes. The WEO rejuvenated mixtures showing lower M_R values than the control mixtures but better than the standard mixtures. The increment of oil level after 13 percent showed a decrease of resistance to moisture damage. Percentage ITS loss values of WEO rejuvenated samples are ranged from 4 to 18 percent. Use of 30 to 50 percent WEO rejuvenated mixes, can save 19.08 to 33.4 percent of materials cost compare to traditional mixes where it is 20.5 to 37.7 percent economical compare to SAE-10 oil rejuvenated mixes. So, the conclusions for WEO rejuvenated mixes can stated as below:

1. Highest mean ITS value of 690.4 Kpa is observed for SAE-10 oil rejuvenated mix. This mix is significantly different from other WEO rejuvenated of mixes. WEO rejuvenated mixes with 30 percent RAP are showing a mean ITS value of 644.4 kpa which is the highest ITS value among all of the WEO rejuvenated mixes. The lowest observed ITS value is 587.2 Kpa for WEO rejuvenated mix with 50 percent RAP. A decreasing trend in ITS value observed due to increase in percentage of RAP in the mixes.
2. WEO rejuvenated mixes have a mean ITS value of 616.8 Kpa which is smaller than the observed ITS value of 686.6 Kpa for the standard rejuvenator SAE-10 oil rejuvenated mix. The maximum means ITS value of 716.3 kpa is observed for 7% SAE-10 oil where

minimum mean ITS value observed for 20 % WEO is 526.4 Kpa. 20% WEO rejuvenated mixes are significantly different from other percentages of rejuvenator.

3. WEO rejuvenated mixes have a mean M_R value of 1664 Mpa which is lower than the observed M_R value of 1845 Mpa for the standard rejuvenator SAE-10 oil rejuvenated mix. The maximum mean M_R value of 2125 Mpa is observed for 7% SAE-10 oil. 7 to 13 percent WEO and 13 percent SAE-10 oil rejuvenated mixes were found with similar effect. The minimum mean M_R value of 1378 Mpa is observed for 20 % WEO and significantly different from other mixes.
4. The maximum mean M_R value of 1810 Mpa is observed for 50 percent RAP mix whereas the minimum mean M_R value is 1710 Mpa for 30 percent RAP mixes. An increasing in M_R value is observed due to increase in percent of RAP, which is an indication of stiffer mix due to presence of RAP. Highest mean M_R value of 1947 Mpa is observed for SAE-10 oil rejuvenated 50 percent RAP mix and the lowest M_R value of 1654 Mpa is observed for WEO rejuvenated 30 percent RAP mix.
5. WEO rejuvenated mix has a mean percent ITS loss value of 8.352 which is significantly smaller than the observed percent ITS loss value of 12.056 for the SAE-10 oil rejuvenated mix. Both mixes are within the specified limit. Percentage of rejuvenator has a significant effect on percent ITS loss. The maximum mean percent ITS loss of 12.648 is observed for 20 % WEO rejuvenated mix. The lowest observed loss is 5.722 percent for 7 percent WEO rejuvenated mix. However, all mixes are showing an ITS loss within the allowable maximum limit.

6. Percent of RAP in mix is significantly affecting the percent ITS loss of mix. Mixes with 50 percent RAP have the highest mean percent ITS loss value of 14.676. The mixes with 30 and 40 percent RAP have a mean percent ITS loss of 8.213 and 7.722 respectively.

5.2 Future Work

The following recommendations are highly important for the further studies of waste oil rejuvenated RAP.

- Here one source of RAP has been studied. Multiple RAP sources should be investigated.
- Some more tests such as cracking test, such as the Semi-circular Bending Test, rutting, fatigue etc., should be investigated.
- Asphalt pavement analyzer, Mechanistic-Empirical Design (MEPDG) or a similar tool can be used to simulate the long-term performance of waste oil rejuvenated pavements.
- To evaluate the performance of waste oil rejuvenated RAP, test section should be constructed, where the performance of these mixes should be monitored under actual traffic, climate and environmental conditions.
- Specifications for the use of high RAP mixes with and without rejuvenators can be developed. It will encourage local contractor and ministry of transportation to use RAP in road construction,

Reference

[1] G. Valdés, F. Pérez-Jiménez, R. Miró, A. Martínez, and R. Botella, “Experimental study of recycled asphalt mixtures with high percentages of reclaimed asphalt pavement (RAP),” *Constr. Build. Mater.*, vol. 25, pp. 1289–1297, 2011.

[2] R. L. Epps, J. A., Little, D. N., Holmgreen, R. J. & Terrel, “Guidelines for Recycling Pavement Materials,” Highway Research Board of the Division of Engineering and Industrial Research, National Academy of Sciences, National Research Council, 1964.

[3] B. S. Hamad, A. A. Rteil, and M. El-Fadel, “Effect of used engine oil on properties of fresh and hardened concrete,” *Constr. Build. Mater.*, vol. 17, no. 5, pp. 311–318, 2003.

[4] G. Valdés, F. Pérez-Jiménez, R. Miró, A. Martínez, and R. Botella, “Experimental study of recycled asphalt mixtures with high percentages of reclaimed asphalt pavement (RAP),” *Constr. Build. Mater.*, vol. 25, no. 3, pp. 1289–1297, 2011.

[5] “Public Roads - Recycled Roadways , January/February 2005 - FHWA-HRT-05-003.”

[6] European Asphalt Pavement Association, “Asphalt in Figures 2011,” Brussels, Belgium, 2012.

[7] “Information Series 138 Asphalt Pavement Industry Survey on Recycled Materials and Warm-Mix Asphalt Usage 2014 5th Annual Survey.”

[8] J. W. Button, D. N. Little, and C. K. Estakhri, “Hot in-Place Recycling of Asphalt Concrete,” *NCHRP Synth. Highw. Pract.*, no. 193, p. 81, 1996.

[9] K. R. Hansen and A. Copeland, “2nd Annual Asphalt Pavement Industry Survey on Reclaimed Asphalt Pavement, Reclaimed Asphalt Shingles, and Warm-Mix Asphalt Usage: 2009–2011,” 2013.

[10] H. M. R. D. Silva, J. R. M. Oliveira, and C. M. G. Jesus, “Are totally recycled hot mix asphalts a sustainable alternative for road paving?,” *Resour. Conserv. Recycl.*, vol. 60, pp. 38–48, Mar. 2012.

[11] Kamel M. A, Al-Bustami N.M, and AlSulami B.T, “Evaluation of the Suitability of Recycled Asphalt Pavement (RAP) for Subbases,” *Int. J. Emerg. Technol. Adv. Eng. Website www.ijetae.com ISO Certif. J.*, vol. 9001, no. 5, 2250.

[12] K.Majidzadeh, “Synthesis of Pavement Recycling: Ministry of Communications of Kingdom of Saudi Arabia.”

[13] S. S. Khan, H. A. Tahha, and Ahmed T. Farouki, “Asphalt Recycling in the kingdom of Saudi Arabia,” 1988.

[14] H. I. Al-Abdul Wahhab, M. G. Baig, I. A. Mahmoud, and H. M. Kattan, “Study of road bases construction in Saudi Arabia using foam asphalt,” *Constr. Build. Mater.*, vol. 26, no. 1, pp. 113–121, 2012.

[15] "Oil - production - Country Comparison - TOP 20." [Online]. Available: http://www.indexmundi.com/g/r.aspx?v=88&t=20. [Accessed: 18-Apr-2017].

[16] Saudi aramco, "Facts & Figures 2014 - Saudi Aramco," 2014.

[17] A. A. Bubshait, "Quality of Pavement Construction in Saudi Arabia," *Pract. Period. Struct. Des. Constr.*, vol. 6, no. 3, pp. 129–136, Aug. 2001.

[18] M. G. Arora and R. K. Abdel, "Laboratory Study on Recycling Potential of Deteriorated Asphalt Pavement in Saudi Arabia," in *Asphalt: Road to 2000; 6th International Asphalt Conference*, 1986.

[19] S. S. Khan, A. T. Farouki, and T. A. Farwana, "Asphalt recycling in the Kingdom of Saudi Arabia: a case study," vol. 3, 1989.

[20] S. Kabir, A. Al-Shayeb, and I. M. Khan, "Recycled Construction Debris as Concrete Aggregate for Sustainable Construction Materials," *Procedia Eng.*, vol. 145, pp. 1518–1525, 2016.

[21] M. Chen, F. Xiao, B. Putman, B. Leng, and S. Wu, "High temperature properties of rejuvenating recovered binder with rejuvenator, waste cooking and cotton seed oils," *Constr. Build. Mater.*, vol. 59, pp. 10–16, 2014.

[22] U. Bagampadde, H. I. A.-A. Wahhab, and S. A. Aiban, "Optimization of Steel Slag Aggregates for Bituminous Mixes in Saudi Arabia," *J. Mater. Civ. Eng.*, vol. 11, no. 1, pp. 30–35, Feb. 1999.

[23] A. Husain and M. M. Assas, "Utilization of Demolished Concrete Waste for New Construction," *Int. J. Civil, Environ. Struct. Constr. Archit. Eng.*, vol. 7, no. 1, 2013.

[24] M. S. M. Innovative Space of Scientific Research Journals and Z. Kaneesamkandi, *Biodegradable waste to biogas: Renewable energy option for the Kingdom of Saudi Arabia*, vol. 4, no. 1. ISSR Journals, 2013.

[25] M. Dalhat and H. A.-A. Wahhab, "Performance of recycled plastic waste modified asphalt binder in Saudi Arabia," *Int. J.*, 2017.

[26] I. Widyatmoko, "Mechanistic-empirical mixture design for hot mix asphalt pavement recycling," *Constr. Build. Mater.*, 2008.

[27] Z. You, J. Mills-Beale, E. Fini, S. W. Goh, and B. Colbert, "Evaluation of Low-Temperature Binder Properties of Warm-Mix Asphalt, Extracted and Recovered RAP and RAS, and Bioasphalt," *J. Mater. Civ. Eng.*, vol. 23, no. 11, pp. 1569–1574, Nov. 2011.

[28] B. Huang, X. Shu, and D. Vukosavljevic, "Laboratory Investigation of Cracking Resistance of Hot-Mix Asphalt Field Mixtures Containing Screened Reclaimed Asphalt Pavement," *J. Mater. Civ. Eng.*, vol. 23, no. 11, pp. 1535–1543, Nov. 2011.

[29] P. S. Kandhal and R. B. Mallick, "Pavement Recycling Guidelines for State and Local

Governments - Participant's Handbook," 1997.

[30] F. L. Roberts, P. S. Kandhal, E. R. Brown, D.-Y. Lee, and T. W. Kennedy, "Hot Mix Asphalt Materials, Mixture Design and Construction," 1991.

[31] X. Shu, B. Huang, and D. Vukosavljevic, "Evaluation of Cracking Resistance of Recycled Asphalt Mixture Using Semi-Circular Bending Test," in *Paving Materials and Pavement Analysis*, 2010, pp. 58–65.

[32] R. Mallick, P. Kandhal, and R. Bradbury, "Using Warm-Mix Asphalt Technology to Incorporate High Percentage of Reclaimed Asphalt Pavement Material in Asphalt Mixtures," *Transp. Res. Rec. J. Transp. Res. Board*, vol. 2051, pp. 71–79, Dec. 2008.

[33] M. Tao and R. Mallick, "Effects of Warm-Mix Asphalt Additives on Workability and Mechanical Properties of Reclaimed Asphalt Pavement Material," *Transp. Res. Rec. J. Transp. Res. Board*, vol. 2126, pp. 151–160, Dec. 2009.

[34] S. C. Somé, A. Pavoine, and E. Chailleux, "Evaluation of the potential use of waste sunflower and rapeseed oils-modified natural bitumen as binders for asphalt pavement design," *Int. J. Pavement Res. Technol.*, vol. 9, no. 5, pp. 368–375, 2016.

[35] M. Tao and R. Mallick, "Effects of Warm-Mix Asphalt Additives on Workability and Mechanical Properties of Reclaimed Asphalt Pavement Material," *Transp. Res. Rec. J. Transp. Res. Board*, vol. 2126, pp. 151–160, Dec. 2009.

[36] M. Nasir, M. Taher, and M. Y. Aman, "An Overview of Reclaimed Asphalt Pavement (Rap) Materials in Warm Mix Asphalt Using Foaming Technology," vol. 11, no. 16, 2016.

[37] "Asphalt Recycling." [Online]. Available: http://asphaltrecycling.com/. [Accessed: 18-Apr-2017].

[38] A. Horvath, "Life-Cycle Environmental and Economic Assessment of Using Recycled Materials for Asphalt Pavements," *Univ. Calif. Transp. Cent.*, 2003.

[39] A. Alkins, B. Lane, and T. Kazmierowski, "Sustainable Pavements: Environmental, Economic, and Social Benefits of In Situ Pavement Recycling," *Transp. Res. Rec. J. Transp. Res. Board*, vol. 2084, pp. 100–103, Dec. 2008.

[40] S. Feih, E. Boiocchi, G. Mathys, Z. Mathys, A. G. Gibson, and A. P. Mouritz, "Mechanical properties of thermally-treated and recycled glass fibres," *Compos. Part B Eng.*, vol. 42, no. 3, pp. 350–358, 2011.

[41] N. Wasiuddin, S. Selvamohan, M. Zaman, and M. Guegan, "Comparative Laboratory Study of Sasobit and Aspha-Min Additives in Warm-Mix Asphalt," *Transp. Res. Rec. J. Transp. Res. Board*, vol. 1998, pp. 82–88, Jan. 2007.

[42] K. A. O 'sullivan and P. A. Wall, "The Effects of Warm Mix Asphalt Additives on Recycled Asphalt Pavement," 2009.

[43] C.-T. Chiu, T.-H. Hsu, and W.-F. Yang, "Life cycle assessment on using recycled materials for rehabilitating asphalt pavements," *Resour. Conserv. Recycl.*, vol. 52, no. 3, pp. 545–556, 2008.

[44] R. S. Mcdaniel, H. Soleymani, R. M. Anderson, P. Turner, and R. Peterson, "NCHRP Web Document 30 (Project D9-12): Contractor's Final Report Recommended Use of Reclaimed Asphalt Pavement in the Superpave Mix Design Method," 2000.

[45] H. R. Paul, "Evaluation of Recycled Projects for Performance," 1995.

[46] M. Zaumanis, R. B. Mallick, and R. Frank, "Determining optimum rejuvenator dose for asphalt recycling based on Superpave performance grade specifications," *Constr. Build. Mater.*, vol. 69, pp. 159–166, 2014.

[47] N. Tran, A. Taylor, and R. Willis, "Effect of Rejuvenator on Performance Properties of HMA Mixtures with High RAP and RAS Contents," 2012.

[48] A. W. Ali, Y. A. Mehta, A. Nolan, C. Purdy, and T. Bennert, "Investigation of the impacts of aging and RAP percentages on effectiveness of asphalt binder rejuvenators," *Constr. Build. Mater.*, vol. 110, pp. 211–217, 2016.

[49] J. Shen, S. Amirkhanian, and B. Tang, "Effects of rejuvenator on performance-based properties of rejuvenated asphalt binder and mixtures," *Constr. Build. Mater.*, vol. 21, no. 5, pp. 958–964, 2007.

[50] T. Bennert, J. Daniel, and W. Mogawer, "Strategies for Incorporating Higher Recycled Asphalt Pavement Percentages," *Transp. Res. Rec. J. Transp. Res. Board*, vol. 2445, pp. 83–93, Dec. 2014.

[51] W. S. Mogawer, A. J. Austerman, R. Kluttz, and S. Puchalski, "Using Polymer Modification and Rejuvenators to Improve the Performance of High Reclaimed Asphalt Pavement Mixtures," *Transp. Res. Rec. J. Transp. Res. Board*, vol. 2575, pp. 10–18, Jan. 2016.

[52] S. Im, F. Zhou, R. Lee, and T. Scullion, "Impacts of rejuvenators on performance and engineering properties of asphalt mixtures containing recycled materials," *Constr. Build. Mater.*, vol. 53, pp. 596–603, 2014.

[53] J.-S. Chen, S.-F. Chen, M.-C. Liao, and S. Wei Huang, "Laboratory Evaluation of Asphalt Blends of Recycling Agents Mixed with Aged Binders."

[54] Y. Ding, B. Huang, X. Shu, Y. Zhang, and M. E. Woods, "Use of molecular dynamics to investigate diffusion between virgin and aged asphalt binders," *Fuel*, vol. 174, pp. 267–273, 2016.

[55] X. Yu, M. Zaumanis, S. dos Santos, and L. D. Poulikakos, "Rheological, microscopic, and chemical characterization of the rejuvenating effect on asphalt binders," *Fuel*, vol. 135, pp. 162–171, 2014.

[56] J. Shen, S. Amirkhanian, and J. A. Miller, "Effects of Rejuvenating Agents on Superpave

Mixtures Containing Reclaimed Asphalt Pavement."

[57] S. I. Sarsam and I. AL-Zubaidi, "Resistance to Deformation under Repeated Loading of Aged and Recycled Sustainable Pavement," *Am. J. Civ. Struct. Eng.*, vol. 1, no. 2, p. 34, 2014.

[58] W. Mogawer, T. Bennert, J. S. Daniel, R. Bonaquist, A. Austerman, and A. Booshehrian, "Performance characteristics of plant produced high RAP mixtures," *Road Mater. Pavement Des.*, vol. 13, no. sup1, pp. 183–208, Jun. 2012.

[59] V. F. C. Lins, M. F. A. S. Araújo, M. I. Yoshida, V. P. Ferraz, D. M. Andrada, and F. S. Lameiras, "Photodegradation of hot-mix asphalt," *Fuel*, vol. 87, no. 15, pp. 3254–3261, 2008.

[60] "NCAT Researchers Explore Multiple Uses of Rejuvenators.," *Asphalt Technology E-News*, vol. 26, no. 1, 2014.

[61] J. S. Chen, C. C. Huang, P. Y. Chu, and K. Y. Lin, "Engineering characterization of recycled asphalt concrete and aged bitumen mixed recycling agent," *J. Mater. Sci.*, vol. 42, no. 23, pp. 9867–9876, Sep. 2007.

[62] Á. García, E. Schlangen, and M. van de Ven, "Properties of capsules containing rejuvenators for their use in asphalt concrete," *Fuel*, vol. 90, no. 2, pp. 583–591, 2011.

[63] M. M. Gui, K. T. Lee, and S. Bhatia, "Feasibility of edible oil vs. non-edible oil vs. waste edible oil as biodiesel feedstock," *Energy*, vol. 33, no. 11, pp. 1646–1653, 2008.

[64] "Learn About Biodiesel | Pacific Southwest: Biodiesel | US EPA." [Online]. Available: https://www3.epa.gov/region9/waste/biodiesel/questions.html. [Accessed: 02-May-2017].

[65] H. Asli, E. Ahmadinia, M. Zargar, and M. Karim, "Investigation on physical properties of waste cooking oil–rejuvenated bitumen binder," *Constr. Build.*, 2012.

[66] M. Math, S. Kumar, and S. Chetty, "Technologies for biodiesel production from used cooking oil—A review," *Energy Sustain. Dev.*, 2010.

[67] N. Özbay, N. Oktar, and N. A. Tapan, "Esterification of free fatty acids in waste cooking oils (WCO): Role of ion-exchange resins," *Fuel*, vol. 87, no. 10, pp. 1789–1798, 2008.

[68] W. N. A. Wan Azahar, M. Bujang, R. P. Jaya, M. R. Hainin, N. Ngadi, M. E. Abdullah, and A. A. Mohamed, "A Review On Application Of Waste Cooking Oil As Rejuvenator In Porous Asphalt Mixture," *J. Teknol.*, vol. 78, no. 4, Mar. 2016.

[69] P. Bailey, H. K., & Philips, "Asphalt Rejuvenation.," US Patent 0034586 A1., 2010.

[70] U. W. Gemma Toop, Sacha Alberici, Matthias Spoettle, Huygen van Steen, "Trends in the UCO market," 2014.

[71] A. Villanueva, S. Ho, and L. Zanzotto, "Asphalt modification with used lubricating oil," *Can. J. Civ. Eng.*, vol. 35, no. 2, pp. 148–157, Feb. 2008.

[72] G. Rusbintardjo, M. R. Hainin, and N. I. M. Yusoff, “Fundamental and rheological properties of oil palm fruit ash modified bitumen,” *Constr. Build. Mater.*, vol. 49, pp. 702–711, 2013.

[73] R. Abro, X. Chen, K. Harijan, Z. A. Dhakan, and M. Ammar, “A Comparative Study of Recycling of Used Engine Oil Using Extraction by Composite Solvent, Single Solvent, and Acid Treatment Methods,” *ISRN Chem. Eng.*, vol. 2013, pp. 1–5, 2013.

[74] M. A. Al-Ghouti and L. Al-Atoum, “Virgin and recycled engine oil differentiation: A spectroscopic study,” *J. Environ. Manage.*, vol. 90, no. 1, pp. 187–195, 2009.

[75] M. El-Fadel and R. Khoury, “Strategies for vehicle waste-oil management: a case study,” *Resour. Conserv. Recycl.*, vol. 33, no. 2, pp. 75–91, 2001.

[76] C. D. Dedene, “Investigation of using waste engine oil blended with reclaimed asphalt materials to improve pavement recyclability,” 2011.

[77] J. Hopmans, “The problem of the processing of spent oil in the member states of EEC,” 1974.

[78] H. M. R. D. Silva, J. R. M. Oliveira, and C. M. G. Jesus, “Are totally recycled hot mix asphalts a sustainable alternative for road paving?,” *Resour. Conserv. Recycl.*, vol. 60, pp. 38–48, 2012.

[79] J. C. Ssempebwa and D. O. Carpenter, “The generation, use and disposal of waste crankcase oil in developing countries: A case for Kampala district, Uganda,” *J. Hazard. Mater.*, vol. 161, no. 2–3, pp. 835–841, Jan. 2009.

[80] S. Tuncalp, “Marketing Intelligence & Planning The Automobile Market in Saudi Arabia: Implications for Export Marketing Planning,” *Mark. Intell. Plan. Int. J. Phys. Distrib. & Mater. Manag. Iss Asia Pacific J. Mark. Logist. Iss Mark. Intell. Plan.*, vol. 11, no. 1, pp. 28–36, 1993.

[81] “Top Markets.” [Online]. Available: http://www.trade.gov/topmarkets/. [Accessed: 19-Apr-2017].

[82] “‘Don’t ban expats from owning 7-seaters’ | Saudi Gazette.” [Online]. Available: http://saudigazette.com.sa/saudi-arabia/dont-ban-expats-owning-7-seaters/. [Accessed: 26-Apr-2017].

[83] “New standards on vehicles in Saudi Arabia from next month - Al Arabiya English.”

[84] “Saudi Arabia Is The 15th Largest Car Market In The World | Motory Saudi Arabia.” [Online]. Available: https://ksa.motory.com/en/news/saudi-arabia-is-the-15th-largest-car-market-in-the-world-1087/. [Accessed: 26-Apr-2017].

[85] S. A. Al-Fouzan, “Using car parking requirements to promote sustainable transport development in the Kingdom of Saudi Arabia,” 2011.

[86] M. F. Ali, F. Rahman, and A. J. Hamdan, “Techno-economic evaluation of waste lube oil

rerefining," *Int. J. Prod. Econ.*, vol. 42, no. 3, pp. 263–273, Apr. 1996.

[87] "Vehicles in use | OICA." [Online]. Available: http://www.oica.net/category/vehicles-in-use/. [Accessed: 07-May-2017].

[88] M. F. Ali, F. Rahman, and A. J. Hamdan, "Techno-economic evaluation of waste lube oil rerefining," *Int. J. Prod. Econ.*, vol. 42, no. 3, pp. 263–273, Apr. 1996.

[89] P. Bailey, H. K., & Philips, "Asphalt rejuvenation," 2009.

[90] M. N. Asian Network for Scientific Information., F. Suja, A. Ismail, and R. A. O. K. Rahmat, *Journal of applied sciences.*, vol. 7, no. 22. Asian Network for Scientific Information, 2004.

[91] C. DeDene, "Investigation of using waste engine oil blended with reclaimed asphalt materials to improve pavement recyclability," *Diss. Master's Theses Master's Reports - Open*, 2011.

[92] N. Tran, A. Taylor, and R. Willis, "Effect of Rejuvenator on Performance Properties of HMA Mixtures with High RAP and RAS Contents," 2012.

[93] H. I. Al-Abdul Wahhab, I. M. Asi, I. A. Al-Dubabe, and M. F. Ali, "Development of performance-based bitumen specifications for the Gulf countries," *Constr. Build. Mater.*, vol. 11, no. 1, pp. 15–22, Feb. 1997.

[94] J. Daniel and A. Lachance, "Mechanistic and Volumetric Properties of Asphalt Mixtures with Recycled Asphalt Pavement," *Transp. Res. Rec. J. Transp. Res. Board*, vol. 1929, pp. 28–36, Jan. 2005.

[95] S. Saliani, A. Carter, and H. Baaj, "Investigation of The Impact of Rap Gradation on The Effective Binder Content in Hot Mix Asphalt," *Can. Soc. Civ. Eng.*, 2016.

[96] A. Basueny, D. Perraton, and A. Carter, "Laboratory study of the effect of RAP conditioning on the mechanical properties of hot mix asphalt containing RAP," *Mater. Struct.*, vol. 47, no. 9, pp. 1425–1450, Sep. 2014.

[97] I. Coas Books, *A Basic Asphalt Emulsion Manual*. Asphalt Institute, 1979.

[98] M. Sabouri, T. Bennert, J. S. Daniel, and Y. R. Kim, "Fatigue and Rutting Evaluation of Laboratory-Produced Asphalt Mixtures Containing Reclaimed Asphalt Pavement," *Transp. Res. Rec. J. Transp. Res. Board*, vol. 2506, pp. 32–44, Nov. 2015.

[99] H. Behbahani, S. Nowbakht, H. Fazaeli, and J. Rahmani, "Effects of Fiber Type and Content on the Rutting Performance of Stone Matrix Asphalt," *J. Appl. Sci.*, vol. 9, no. 10, pp. 1980–1984, Oct. 2009.

[100] Z. Zhang, R. Roque, B. Birgisson, and B. Sangpetngam, "Identification and Verification of A Suitable Crack Growth Law," *J. Assoc. Asph. Paving Technol.*, vol. 70, 2001.

[101] S. Tayfur, H. Ozen, and A. Aksoy, "Investigation of rutting performance of asphalt mixtures containing polymer modifiers," *Constr. Build. Mater.*, vol. 21, no. 2, pp. 328–

337, 2007.

[102] B. Huang, G. Li, and L. N. Mohammad, “Analytical modeling and experimental study of tensile strength of asphalt concrete composite at low temperatures,” *Compos. Part B Eng.*, vol. 34, no. 8, pp. 705–714, 2003.

[103] X. Shu, B. Huang, and D. Vukosavljevic, “Laboratory evaluation of fatigue characteristics of recycled asphalt mixture,” *Constr. Build. Mater.*, vol. 22, no. 7, pp. 1323–1330, 2008.

[104] B. V. Kök and H. Çolak, “Laboratory comparison of the crumb-rubber and SBS modified bitumen and hot mix asphalt,” *Constr. Build. Mater.*, vol. 25, no. 8, pp. 3204–3212, 2011.

[105] A. M. Putri and L. B. Suparma, “Laboratory Study On The Durability Characteristics (Moisture Damage Evaluation) Of Asphalt Concrete Wearing Course (AC-WC) Utilizing Bantak And Clereng As Aggregate (Using Marshall Methods),” *J. East. Asia Soc. Transp. Stud.*, vol. 8, pp. 1555–1567, 2010.

[106] N. S. Mashaan and M. R. Karim, “Evaluation of permanent deformation of CRM-reinforced SMA and its correlation with dynamic stiffness and dynamic creep.,” *ScientificWorldJournal.*, vol. 2013, p. 981637, 2013.

[107] J. S. Carvajal Munoz, F. Kaseer, E. Arambula, and A. Epps Martin, “Use of the Resilient Modulus Test to Characterize Asphalt Mixtures with Recycled Materials and Recycling Agents,” *Transp. Res. Rec. J. Transp. Res. Board*, vol. 2506, pp. 45–53, Nov. 2015.

[108] S. Oruc, F. Celik, and M. V. Akpinar, “Effect of Cement on Emulsified Asphalt Mixtures,” *J. Mater. Eng. Perform.*, vol. 16, no. 5, pp. 578–583, Sep. 2007.

[109] T. Kennedy and I. Perez, “Preliminary Mixture Design Procedure for Recycled Asphalt Materials,” in *Recycling of Bituminous Pavements*, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959: ASTM International, 1978, pp. 47-47–21.

[110] K. L. N. Puga, “Rheology and performance evaluation of Polyoctenamer as Asphalt Rubber modifier in Hot Mix Asphalt,” *Grad. Theses Diss.*, 2013.

[111] P. E. Sebaaly, “Comparison of Lime and Liquid Additives on the Moisture Damage of Hot Mix Asphalt Mixtures,” 2007.

[112] D. C. on B.-A. C. to M. S. R. Transportation Research Board (Washington and D. R. Jones IV, *Moisture Sensitivity of Asphalt Pavements - a National Seminar : 2003 : San Diego, Calif.* TRB, 2003.

[113] S. Zhao, B. Huang, X. Shu, and M. Woods, “Comparative evaluation of warm mix asphalt containing high percentages of reclaimed asphalt pavement,” *Constr. Build. Mater.*, vol. 44, pp. 92–100, 2013.

[114] F. Moghadas Nejad, A. Azarhoosh, G. H. Hamedi, and H. Roshani, “Rutting performance prediction of warm mix asphalt containing reclaimed asphalt pavements,” *Road Mater. Pavement Des.*, vol. 15, no. 1, pp. 207–219, Jan. 2014.

[115] A. Copeland, “Reclaimed Asphalt Pavement in Asphalt Mixtures: State of the Practice,” 2011.

[116] A. Zofka, M. Marasteanu, T. R. Clyne, X. Li, and O. Hoffman, “Development of Simple Asphalt Test for Determination of RAP Blending Charts,” 2004.

[117] R. S. McDaniel, G. A. Huber, and V. Gallivan, “Conserving Resources and Quality with High RAP Content Mixes,” *HMAT Hot Mix Asph. Technol.*, vol. 11, no. 6, 2006.

Appendix

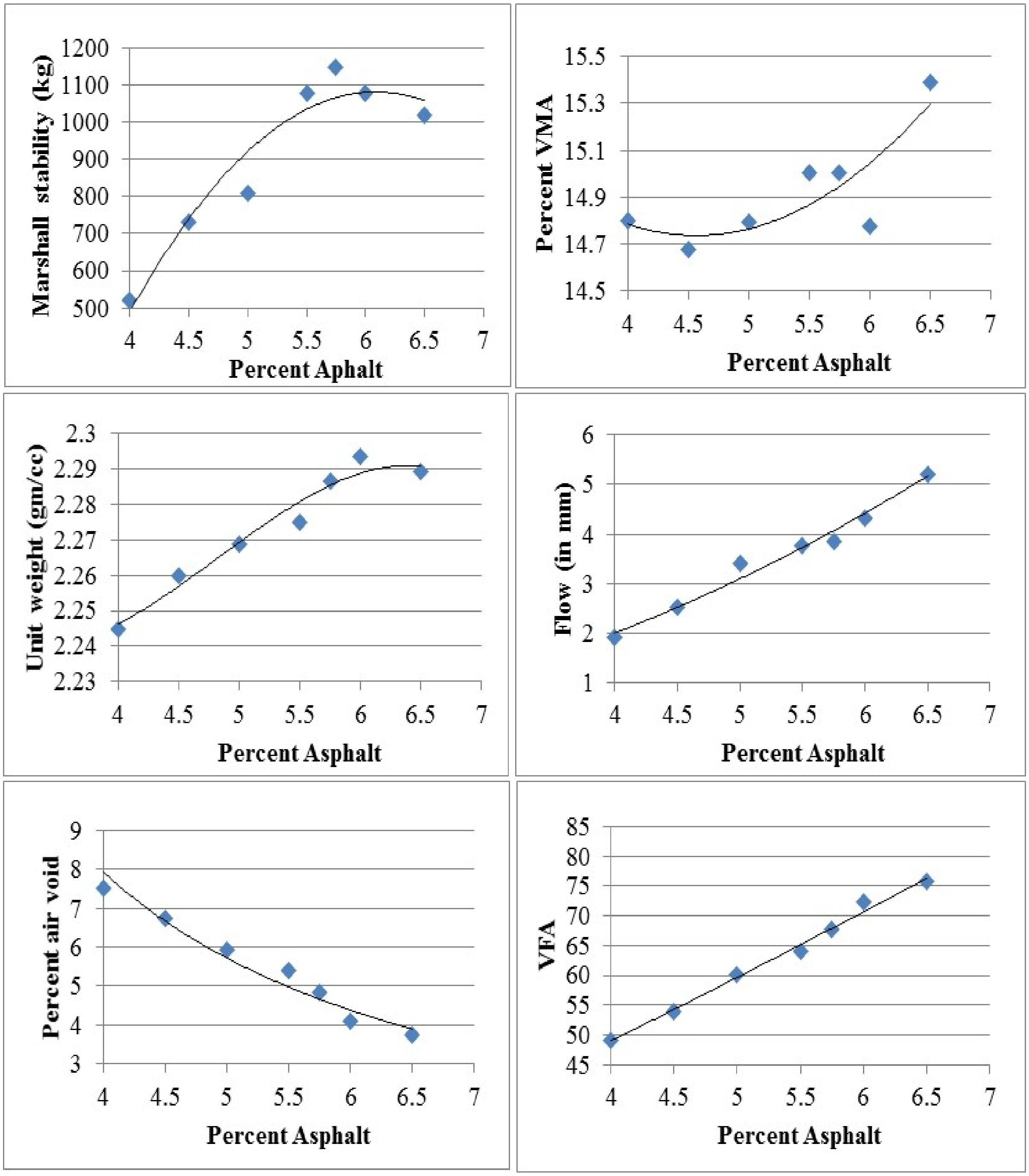


Figure 1: Marshall Mix design for Standard mix

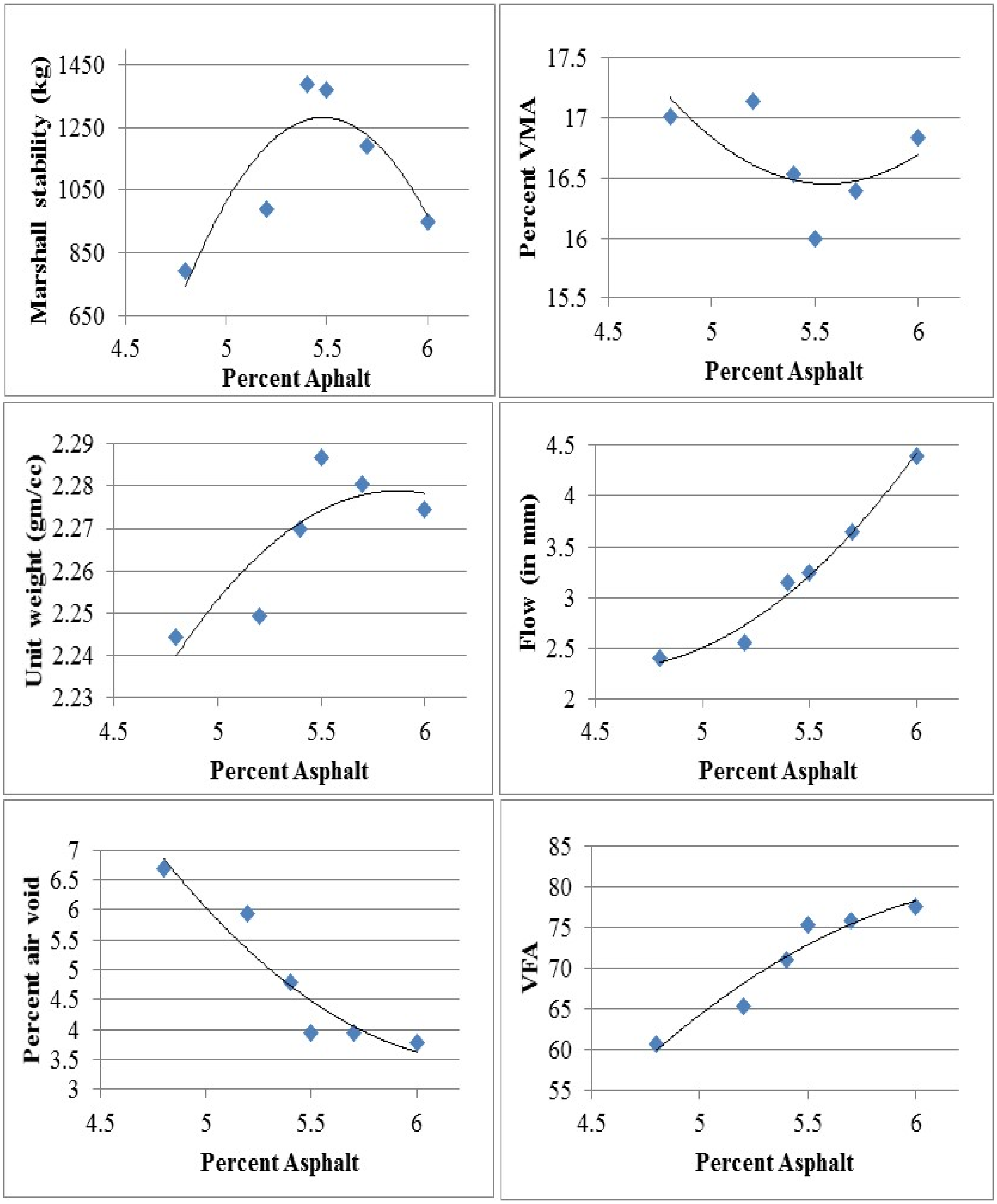


Figure 2: Marshall Mix design for 30 percent RAP mix rejuvenated by SAE-10 oil

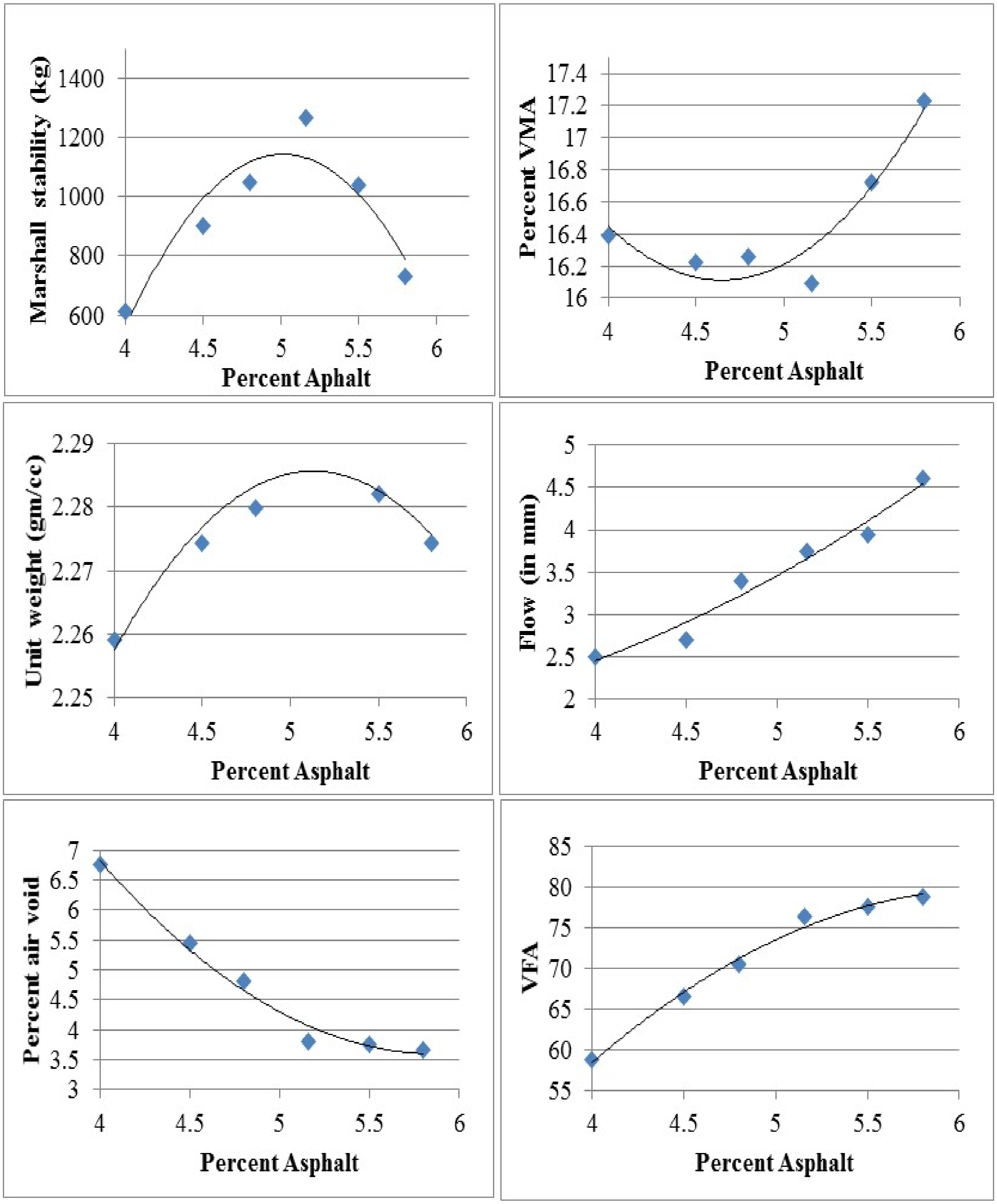


Figure 3 : Marshall Mix design for 40 percent RAP mix rejuvenated by SAE-10 oil

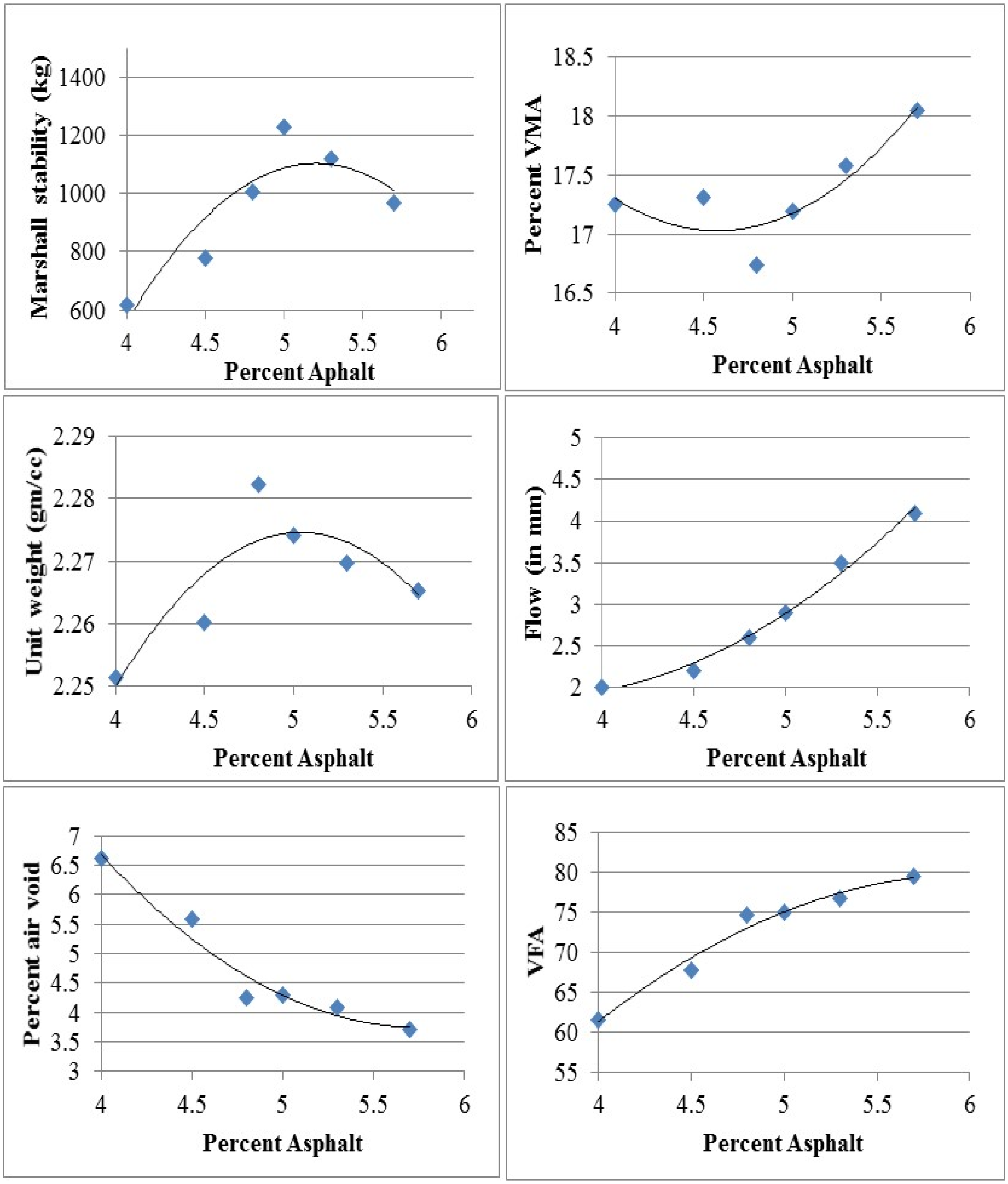


Figure 4 : Marshall Mix design for 50 percent RAP mix rejuvenated by SAE-10 oil

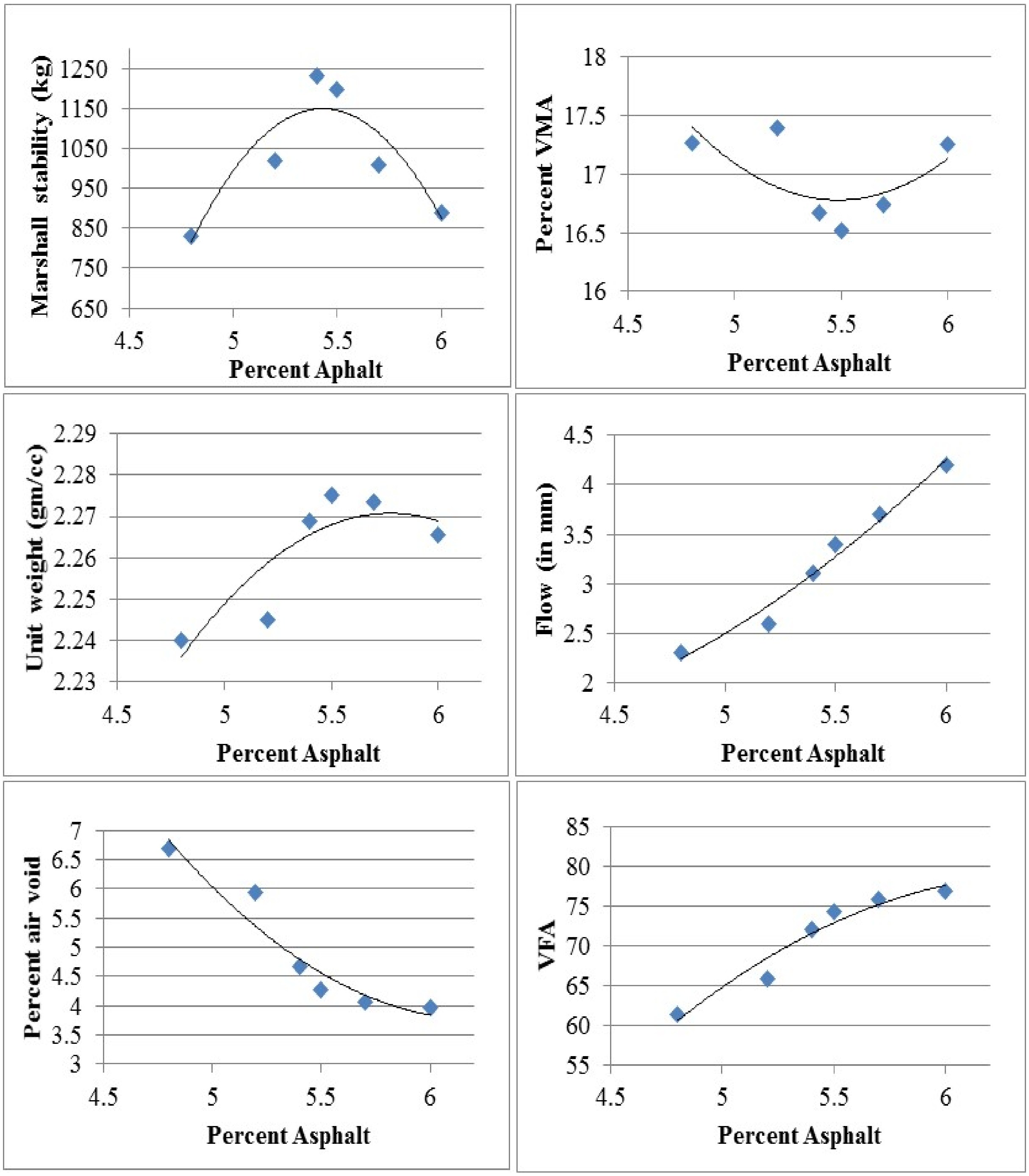


Figure 5 : Marshall Mix design for 30 percent RAP mix rejuvenated by WCO

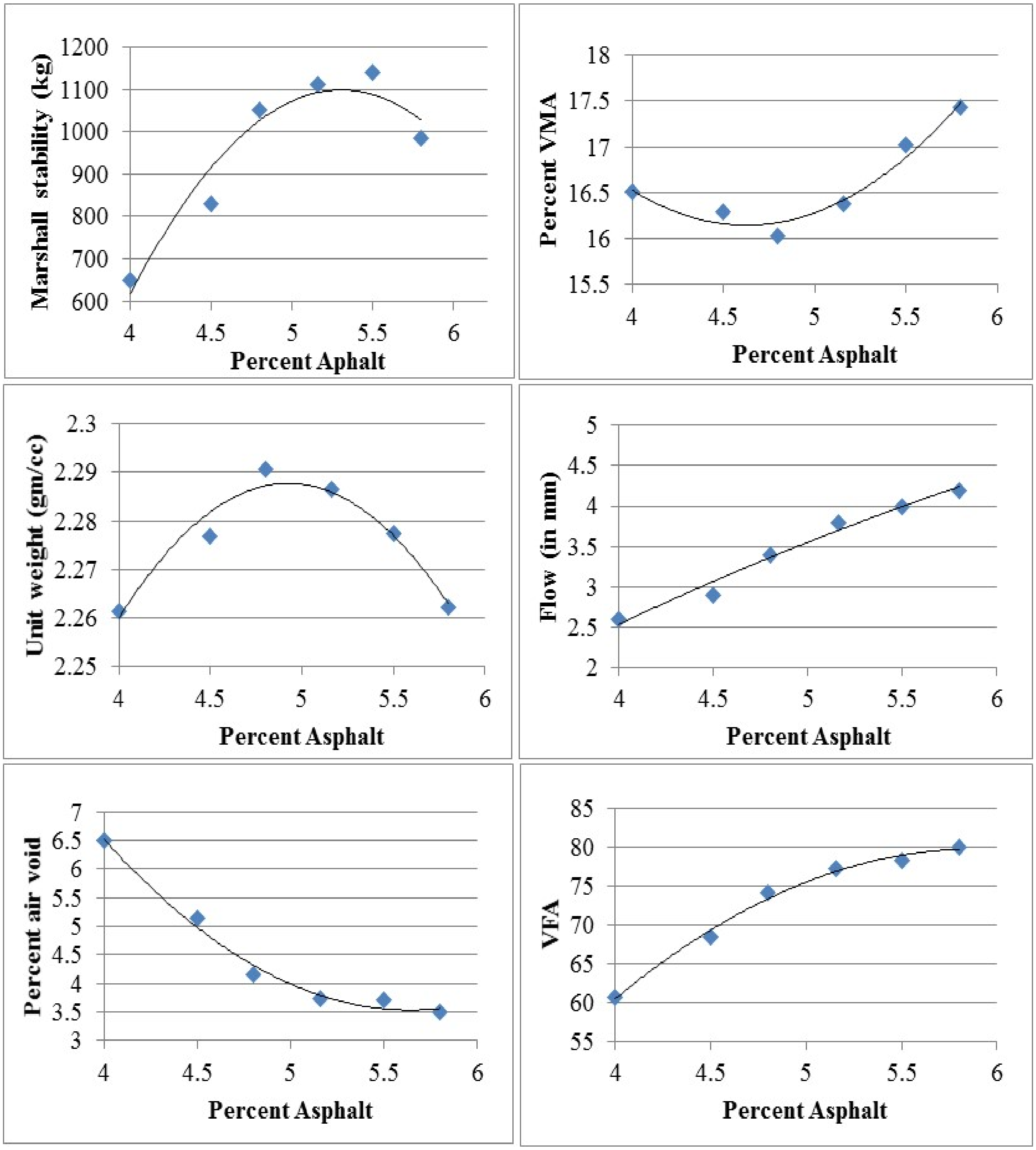


Figure 6 : Marshall Mix design for 40 percent RAP mix rejuvenated by WCO

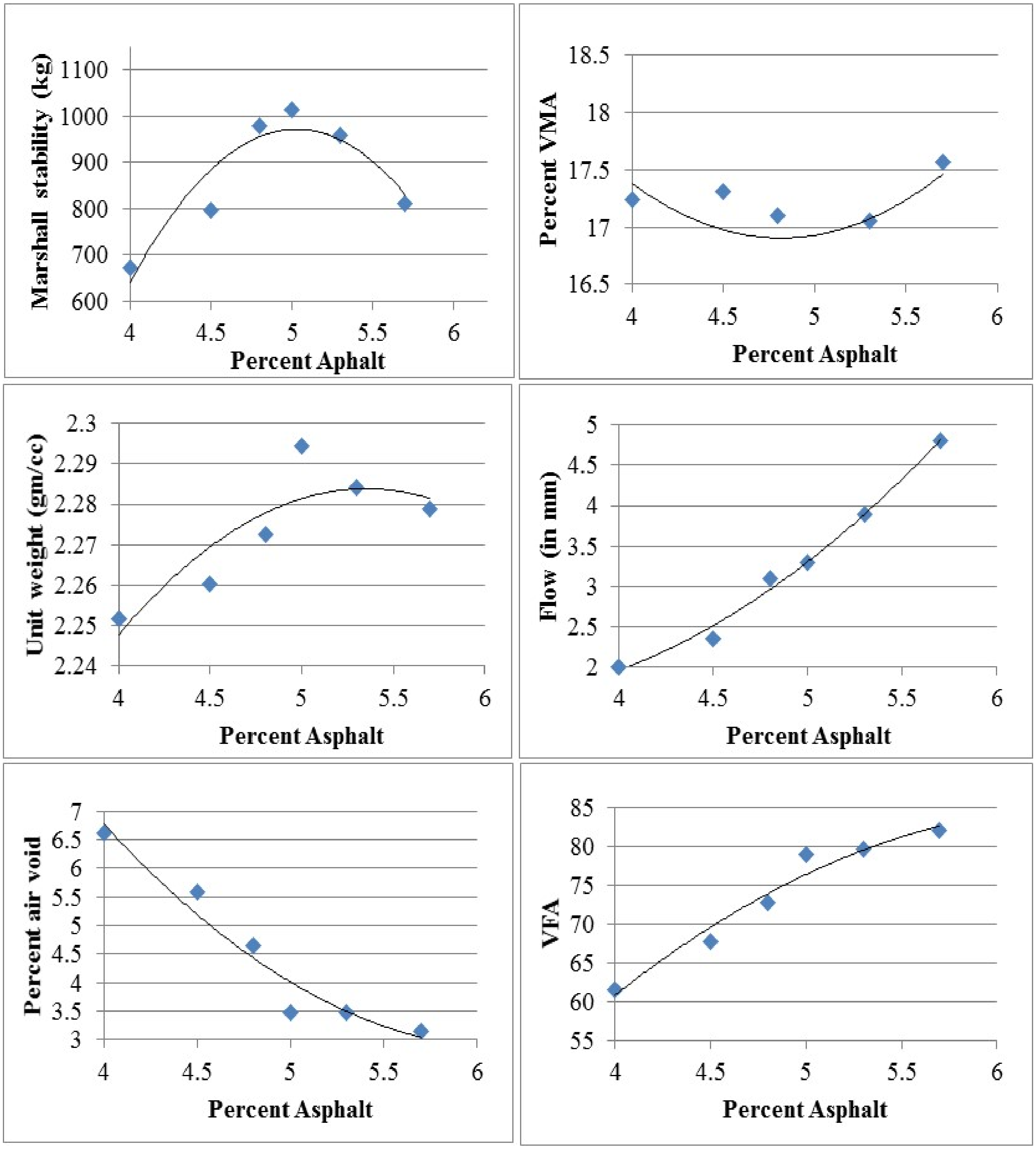


Figure 7 : Marshall Mix design for 50 percent RAP mix rejuvenated by WCO

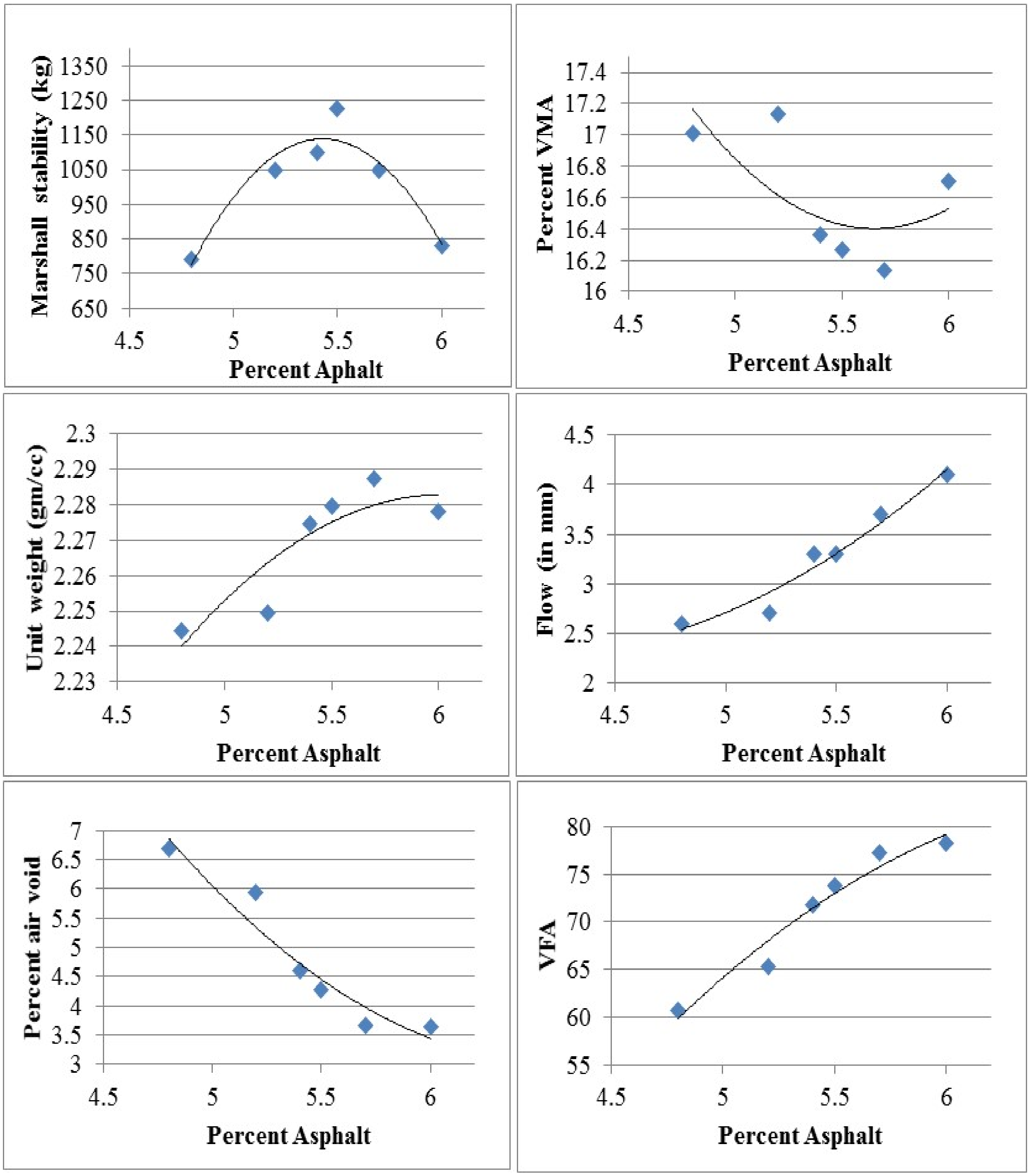


Figure 8 : Marshall Mix design for 30 percent RAP mix rejuvenated by WEO

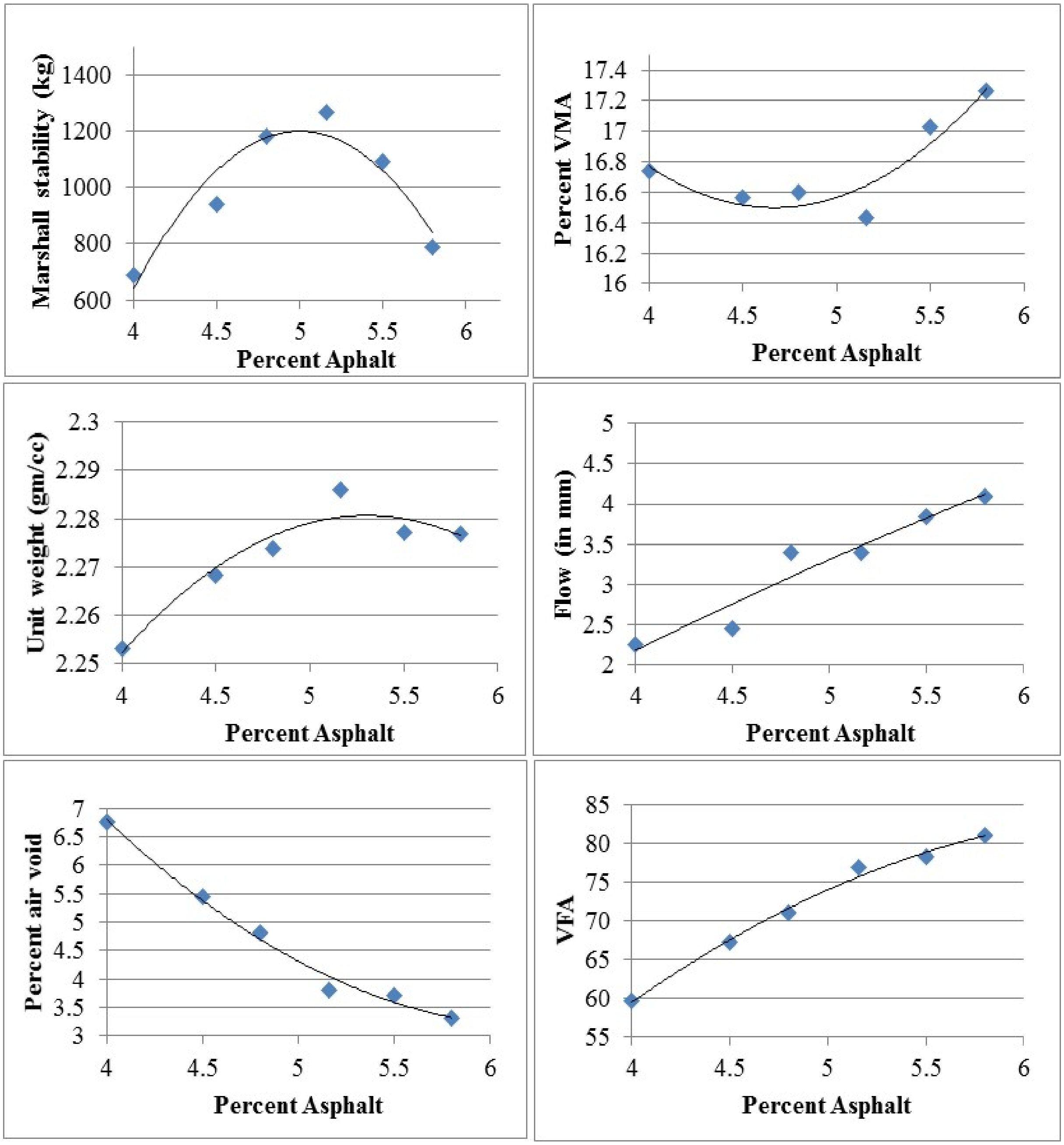


Figure 9: Marshall Mix design for 40 percent RAP mix rejuvenated by WEO

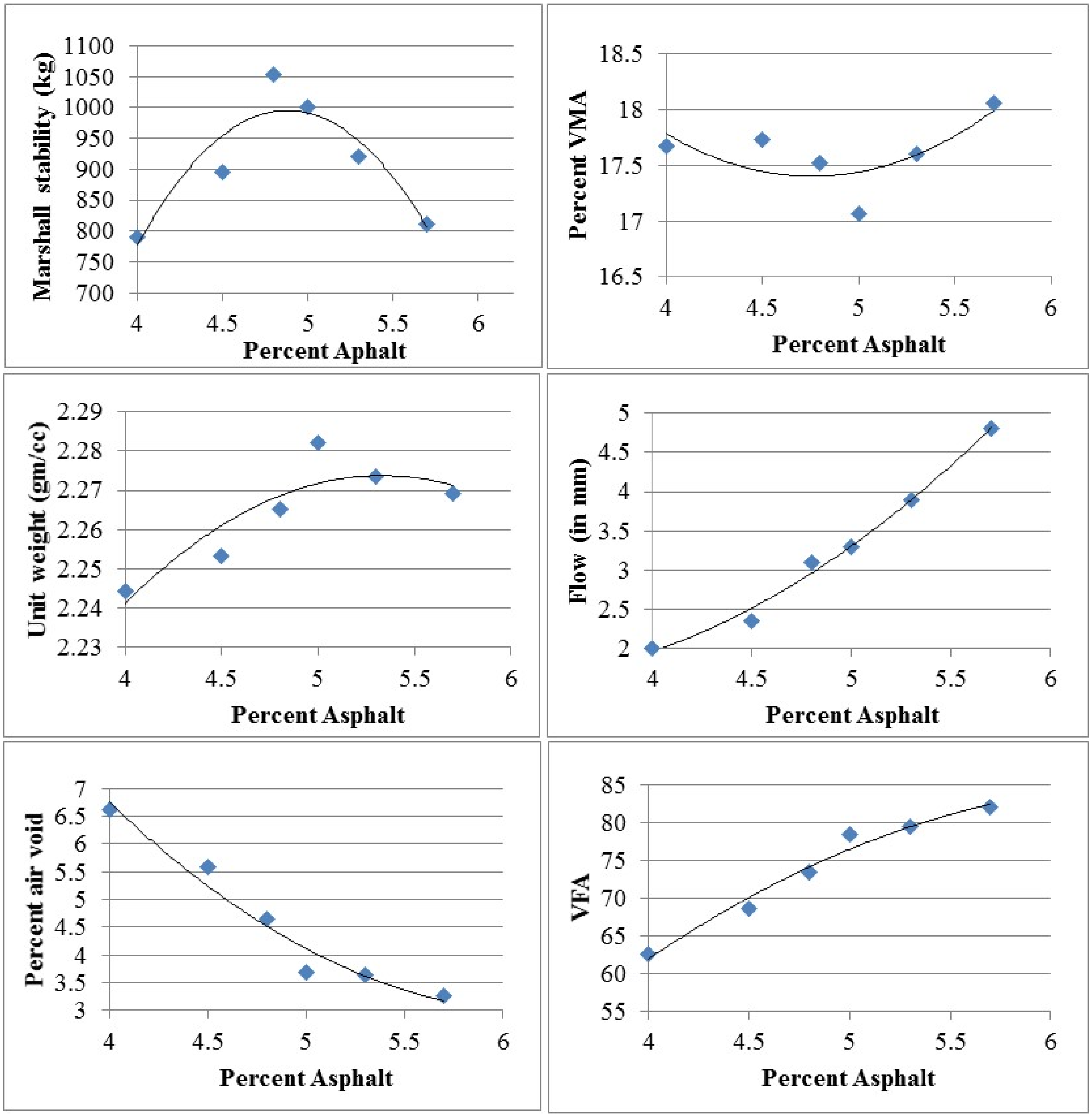


Figure 10: Marshall Mix design for 50 percent RAP mix rejuvenated by WEO

Vitae

Name	:Abdullah Al Mamun
Nationality	:Bangladeshi
Date of Birth	:8/15/1989
Email	:g201401740@kfupm.edu.sa, mamun.khan86@yahoo.com
Address	:Dhaka, Bangladesh
Academic Background	:Received B.Sc. in Civil Engineering from Bangladesh University of Engineering & Technology (BUET), Bangladesh in 2012. He joined M.Sc. in Civil and Environmental Engineering Department at King Fahd University of Petroleum and Minerals in August, 2014.
Research Interests	:Pavement Engineering, Moisture damage of HMA, Optimization, Recycling.